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IEAGHG

CO_2 Transport and Storage Availability

Technical Report 2025-09
November 2025

IEAGHG

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CONTACT DETAILS

Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org
Internet: www.ieaghg.org

Address: IEAGHG, Pure Offices,
Cheltenham Office Park, Hatherley Lane,
Cheltenham, GL51 6SH, UK

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This report describes work undertaken by TNO, SCCS and SINTEF on behalf of IEAGHG. The principal researchers were:

- Filip Neele, TNO
- Suzanne Hurter, TNO
- Stefan Belfroid, TNO
- Elisa Calignano, TNO
- Wouter Janssen, TNO
- Navraj Singh Ghaleigh, SCCS
- Marsaili Van looy, SCCS
- Ali Hassanpouryouzband, SCCS
- Ciara Coughlan, SCCS
- Aya El Samad, SCCS
- Hasan Muslemani, SCCS
- Romain F H Viguier, SCCS
- R Stuart Haszeldine, SCCS
- Ragnhild Skagestad, SINTEF
- Rune Mathisen, SINTEF
- Jon Hovland, SINTEF

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The IEAGHG manager for this report was: Nicola Clarke. The expert reviewers for this report were:

- Julia Race, University of Strathclyde, UK
- Hannah Galbraith-Olive, ERM
- Matthias Imhof, Exxon Mobil
- Marion Wurzel, Exxon Mobil
- Kylie Bishop, Exxon Mobil
- Richard Deutsch, DESNZ, UK
- Lydia Rycroft, DESNZ, UK
- Bailian Chen, Los Alamos National Laboratory, USA
- Tim Dixon, IEAGHG

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Report Overview:

CO_2 Transport and Storage Availability

IEA/CON/23/301

Introduction

High availability of CO_2 Transportation and Storage (T&S) networks will be essential for maximising the benefits of Carbon Capture Utilisation and Storage (CCUS) systems, and are an important aspect of commercial contracts between emitters and T&S operators. Planned or unexpected downtime in the T&S system has implications for the emitters, both commercially and potentially environmentally if they need to vent CO_2 to the atmosphere. There may also be venting/outage challenges when crossing state or national borders.

The objective of this study is to investigate realistic rates of CO_2 T&S operational availability that may be achievable for future systems, with a focus primarily on pipeline transportation and storage within sedimentary basins (saline aquifers and depleted fields).

This study was undertaken by TNO with SINTEF and SCCS.

Key Messages

- At the T&S network level, the requirements of the injection wells place the most constraints on the system for safe operations.

- A connection from a single supplier to a single storage location will, in theory, be more vulnerable to intermittent or fluctuating CO_2 supply, and capture is limited to the availability of storage.
- Designing for a system with terminals and multiple sources and storage sites with a possibility for overcapacity makes the system more robust and flexible.
- The costs for over-sizing infrastructure are potentially high.
- A complex system will likely require more extensive monitoring and supervision to maintain and optimise its operation.
- Operational time and maintenance schedules for existing networks are not readily available in open sources, but would be a valuable dataset for planning operations.
- Existing CO_2 T&S networks have a range of different configurations and operating conditions, and future networks are likely to become increasingly complex with a wider range of operating conditions. These will partly depend on the phase of CO_2 transported, the location of the network (onshore or offshore), the type of pipeline (insulated vs non-insulated), the type of reservoir, and the complexity of the network.
- Downtime can potentially be minimised in the T&S network by designing for a degree of redundancy. Therefore, operations may not need to slow down or shut down, provided sufficient redundancy is built into the network. This can be achieved by building spare capacity into components of the CCUS chain. There is often a trade-off between the chance of an element failing and the costs of installing redundant capacity.
- Both tubing design and downhole chokes play a crucial role in managing CO_2 injection flexibility while ensuring safe and efficient well operations in depleted gas reservoirs.
- Standardising liability frameworks, ownership transfer rules, and CO_2 purity standards could create a more cohesive international CCUS market and reduce risks associated with cross-border transport.

Scope

The objective of this study is to investigate realistic rates of CO_2 T&S operational availability that may be achievable for future systems. By looking at primarily pipeline transportation, the study aims to:

- Review existing CO_2 transportation networks and CO_2 storage sites to assess achieved availability rates and approaches to maximise availability in offshore and onshore saline and depleted oil and gas fields.

- Review other relevant pipeline transportation networks and compare availability rates and best practices.
- Provide a detailed assessment of options for the design and operation of T&S networks to maximise availability.
- Review the current regulatory approaches across a range of jurisdictions and implications to venting/outages. This may also consider any challenges crossing state or national borders in the transport of CO_2.
- Consider the interaction between commercial and funding models.

Conclusions

The following main conclusions are drawn from this study.

System Availability and Flexibility

Variability in CO_2 supply and composition from industrial sources presents challenges to system availability, making flexibility crucial. Key gaps exist in understanding sector-specific CO_2 supply variations. Standardisation of CO_2 specification is needed, with ongoing efforts by international bodies. Flexibility can be improved through buffering techniques like temporary storage, though cost considerations are significant. Injection system design to accommodate fluctuations is influenced largely by reservoir conditions. Redundancies in compressor stations and injection wells can mitigate risks but require cost-benefit analysis. Lessons from early CCUS projects should be shared to optimise future systems.

Network Optimisation

As CCUS expands into large multi-user networks, optimising operating conditions is essential for technical and economic efficiency. Managing pressure differences between injection wells is key, requiring a network-wide rather than individual well-based approach. System resilience improves when excess flow can be redistributed in case of well failure. Multi-user CCUS projects face contractual challenges, including capacity allocation and outage management, which can be mitigated by standardised agreements and centralised bookkeeping.

Regulatory Considerations

Regulatory approaches differ globally, with the EU enforcing strict CCUS regulations, while North America adopts a more flexible approach, often linked to Enhanced Oil Recovery (EOR). Governments can offer support for CCUS by streamlining permitting and ensuring third-party access to infrastructure for a fee. Expanding carbon pricing mechanisms like the EU Emissions Trading System (EU ETS) to include all transport modes (pipelines, ships, etc.) and aligning international carbon markets remains challenging but would enhance economic viability.

Towards an International CCUS Market

CO_2 transport and storage face regulatory inconsistencies across countries. While some cross-border projects are emerging in Europe and Asia, legal and logistical challenges persist. Standardising liability frameworks, ownership transfer rules, and CO_2 purity standards could create a more cohesive international CCUS market and reduce risks associated with cross-border transport.

Expert Review

This report was reviewed by eight external expert reviewers from five organisations, including government, industry and academia. On the basis of suggestions made by the reviewers, there was a restructure and reordering of some elements to avoid duplication and enhance the flow of the document and emphasise the objectives. Individual comments in the document were addressed, and both saline and depleted fields were incorporated as suggested, as were on and offshore examples. The lack of information available from existing projects and on achieved availabilities and target availabilities for planned projects was noted, and the authors have been clear that this information was unfortunately not available. The policy section has been restructured, and a deeper dive into APAC regions has been conducted as a result of suggestions by the reviewers.

Recommendations

- Open access to achieved availability rates of CO_2 capture and storage of operational projects would be a valuable resource for planning future networks.
- It would be useful to harmonise liability frameworks for CO_2 transport across all modes, ensuring consistency and reducing legal uncertainty.
- Regarding facilitating an open-access cross-border CO_2 transport network, the authors recommend adopting a common carrier model for CO_2 pipelines, especially for publicly funded projects, to ensure equitable access.
- It is recommended to establish clear guidelines for CO_2 ownership and liability transfer across the CCUS value chain to reduce uncertainties and disputes in cross-border operations.

CO_2 Transport and Storage Availability

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Energy & Materials Transition
www.tno.nl
+31 88 866 42 56
info@tno.nl

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CO_2 Transport and Storage Availability

Author(s)	TNO Wouter Janssen, Filip Neele, Stefan Belfroid SCCS Navraj Singh Ghaleigh, Marsaili Van Looy, Ali Hassanpouryouzband, Ciara Coughlan, Aya El Samad, Hasan Muslemani, Romain F. H. Viguier, R. Stuart Haszeldine SINTEF Ragnhild Skagestad, Rune Mathisen, Jon Hovland

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Glossary

BECCS	Bio-energy in combination with carbon capture and storage
CC(U)S	Carbon capture (utilization) and storage
CS	Carbon Storage
CO_2-EOR	Enhanced oil recovery through the injection of CO_2 into an oil field
CTBO	Carbon Takeback Obligation
DACCS	Direct Air Capture in combination with carbon storage
EC	European Commission
EU-ETS	Emission trading scheme in the EU
EU	European Union
ESD	Emergency Shutdown
JV	Joint Venture
kt	Kilotonne
ktpa	Kilotonne per annum
LLMC	Limitation of Liability for Maritime Claims
Mt	Megatonne (million tonnes)
Mtpa	Megatonne per year
NZIA	Net Zero Industry Act (in Europe)
PCI	Projects of Common Interest (in Europe)
PI	Productivity Index [(kg/s)/bar]
PPP	Private Public Partnership
SSSV	Subsurface Safety Valve
T&S	Transport and storage
TVD	True Vertical Depth [m]
U	Heat transfer coefficient [W/m^2 K]

1. Introduction

Carbon Capture and Storage (CCS) is a crucial technology in society's current mission to reduce the emission of greenhouse gases to the atmosphere and limit global warming to a maximum of 1.5 °C, as set out by the Paris Agreement[1]. CCS is recognised as an indispensable climate mitigation instrument as achieving a global net zero scenario will be virtually impossible without these technologies[2]. Deployment of CCS technologies is gaining momentum in some parts of the world, for instance, by 2021, 20 European countries had already included CCS as a climate mitigation measure in their national energy and climate plans[3]. CCS projects are already under development worldwide – many of these projects plan to be operational before 2030[4]. Transport networks are needed to connect CO_2 emitters to geological storage projects. Transport projects currently under development differ in transport modality (pipeline, ship, truck or train), size and complexity (ranging from a "one-dimensional" pipeline to a single source to multiple sources connected to several sinks through a backbone).

In order to optimally benefit from CCS technology, maximising transport and storage (T&S) networks' availability rates and thus minimising downtime is important. Unavailability of CO_2 transport and storage systems, especially for an extended period of time, can have undesirable consequences. Firstly, this may lead to venting of greenhouse gases which has obvious environmental implications. Moreover, venting of CO_2 can be costly, especially in jurisdictions where greenhouse gases emissions have been priced, for example through the EU-ETS or national carbon levies. Ultimately, unavailability of T&S systems could lead to interruptions of production processes in hard-to-abate sectors which have no alternatives to CCS to reduce carbon emissions. Implications may extend to product quality standards being compromised on (e.g. unable to meet required/desired carbon intensity for blue hydrogen) which would have commercial implications. Downtime might also be problematic for parties that have received public funding for their project, when funding is linked to emission reduction targets that need to be met.

This work was undertaken by TNO, SINTEF and SCCS for the IEA Greenhouse Gas R&D Program (IEAGHG). This study assesses realistic rates of CO_2 transport and storage operational availability in future systems. This study focuses primarily on pipeline projects and is organised in the following sections:

- Section 1 sets the stage for the study, provides the background and describes the conditions that (may) lead to system outage.
- Section 2 investigates both CO_2 networks as well as analogue gas networks in different countries worldwide in order to establish what approaches have previously been taken to handle CO_2 supply rate variability and optimise system uptime. Variability in both supply and composition are important topics covered.
- Section 3 provides an overview of the technical options to improve system flexibility, as well as their limitations. Section 3 also includes a dynamic simulation of a network experiencing both supply variability as well as disruptions at the injection site.
- Section 4 dives into the interaction between regulatory and commercial aspects and T&S system availability while also discussing proposed contractual implementations (in Heads of Terms) for the cooperation between emitters and T&S operators in an integrated network setting.
- Section 5 offers a discussion on optimal T&S system availability.
- Section 6 draws conclusions based on the results and insights from this body of work, aimed at project developers as well as policy makers.

1.1. Setting the scene

As the necessity for climate change mitigation increases, worldwide investment in carbon capture and storage solutions grows[1]. While currently CO_2 injection is still mostly performed to enhance hydrocarbon production (enhanced oil recovery, enhanced gas recovery), CCS projects are currently also being initiated with the sole purpose of permanent storage of CO_2. Important drivers behind this development are regulatory (e.g. reduction of emission allowances under EU ETS, net zero permitting requirements for new gas reservoirs under the Safeguard Mechanism in Australia), increased value placed upon CO_2 emissions (e.g. EU ETS, national carbon levies) and incentive mechanisms such as the Inflation Reduction Act in the USA. There is also a growing awareness that permanent storage of biogenic or atmospheric CO_2 will play an essential role in generating negative emissions, in order to offset residual emissions of industries that are technically difficult and/or prohibitively costly to decarbonise otherwise. Also, the more CO_2 emissions overshoot beyond the Paris Agreement levels, the more negative emissions technology will be needed to compensate for this delayed decarbonisation[5].

As part of their broader climate change mitigation strategy, an increasing number of governments are committing to CCS to decarbonise hard-to-abate sectors and/or generate negative emissions. Examples are:

- Recent European legislation such as the European Green Deal and the Net Zero Industry Act, underline the need for development of transport and storage networks for CO_2. Through the Net Zero Industry Act, the EU has defined a CO_2 injection capacity target of 50 Mtpa in 2030, excluding CO_2 storage meant to enhance hydrocarbon production[6]. By 2050, the estimated market demand for carbon storage capacity in Europe is between 100-300 Mtpa[7]. However, to achieve net carbon neutrality in 2050, the European Commission estimates a need for available carbon capture capacity of 550 Mtpa, including capture to generate negative emissions[6].
- China too has indicated it will commit to carbon neutrality. China currently emits almost one-third of the global emissions of CO_2 and therefore is expected to have a significant demand for CCS technology in the future. Projections show CCUS demand in China in the range of 58-147 Mtpa in 2030 and 2.11-2.53 Gtpa in 2060 of which almost 500-800 Mtpa consists of negative emission technologies such as DACCS and BECCS[8]. By 2030, China plans to host pilot and demonstrator projects across multiple industrial sectors as well as the thermal power sector. Full-scale commercial CCS projects are expected to develop rapidly after 2030 in China.
- In the US, the Inflation Reduction Act provides critical updates to the 45Q tax credit, which incentivises the use of CCS technologies by offering up to $85 per ton of CO_2 captured and permanently stored in geological formations, thereby making CCS technologies significantly more accessible to investors and project developers[9].
- The Japanese government has released a CCUS Long-Term Roadmap which aims at storing between 120 and 240 Mtpa of CO_2 by 2050[10].
- In Saudi Arabia, a CCS hub in Jubail aims to store 44 Mtpa by 2035, captured from hard-to-abate sections including gas processing, petrochemicals, cement, refining and steel manufacturing[1].

While the CCS industry scales up, the complexity of associated T&S networks will likely increase. T&S networks are expected to become increasingly interconnected and diverse in the transport modalities, as a result of the uneven distribution of CCS deployment needs and geological storage locations.

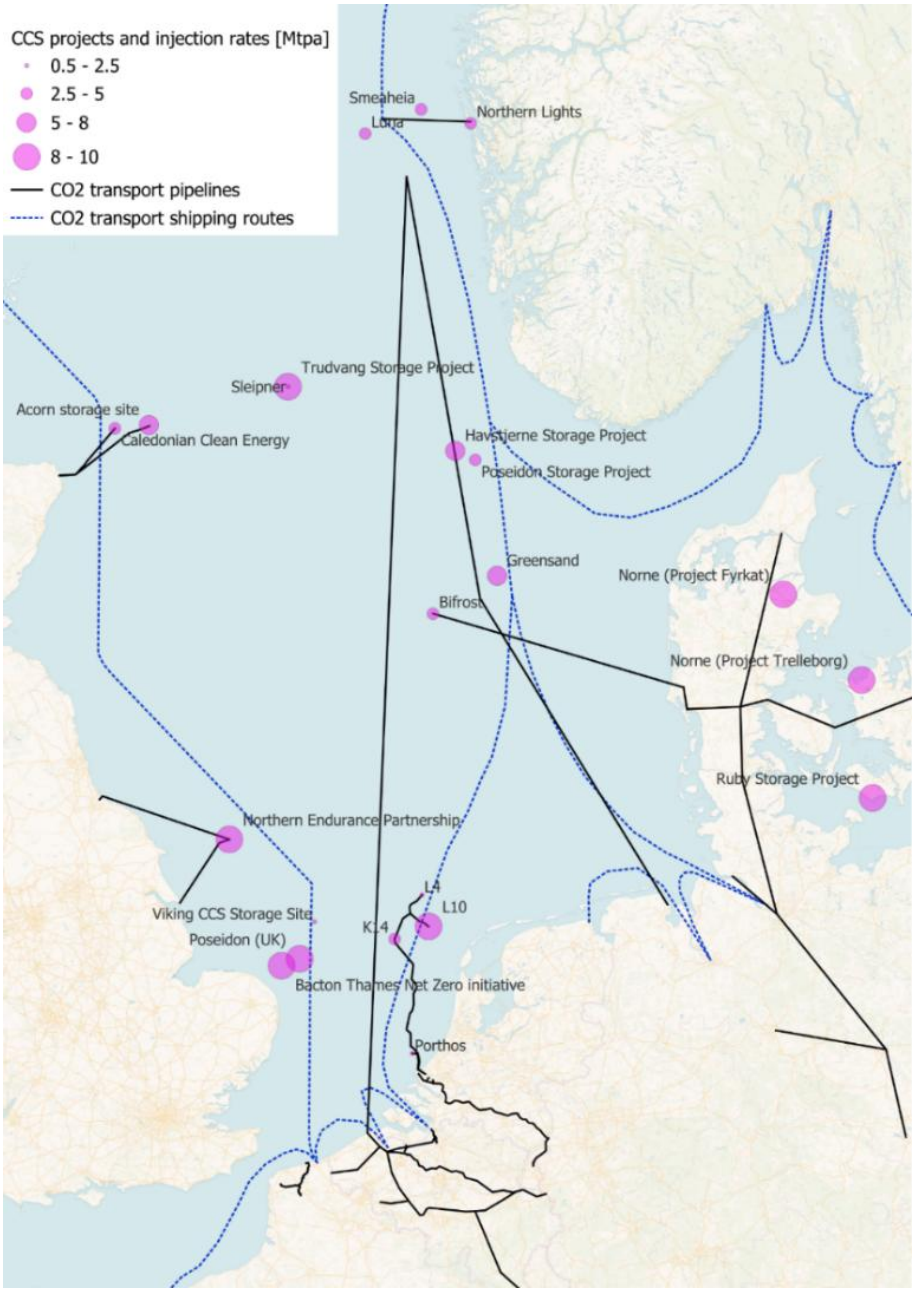

Figure 1. Representation of storage projects and transport routes expected to be in place by 2030. Not all of the transport routes shown may be in place by 2030. Some routes are shown both as ship and pipeline routes. At the time of writing this report, it was not possible to select the more likely transport mode. The shipping routes reflect the Northern Light's PCI plans. Source: TNO internal, 2024.

Figure 1 and Figure 2 show separate projections of transport and storage networks for CO_2 in the European North Sea in 2030 and 2050, respectively. An upscale of storage locations can be observed between 2030 and 2050. Northwest Europe can serve as an example of an area that has the potential of developing into a multi-modal, interconnected, and cross-border network. The European Commission's PCI-list (Projects of Common Interest)[11] contains multiple projects for large-scale CCS infrastructure containing cross-border pipeline connections (e.g. CO2TransPorts, EU2NSEA, Delta Rhine Corridor). Towards 2050, connections are projected to be made between the mainland Northwest

European countries and European countries with large CO_2 storage potential such as Norway and the United Kingdom.

Moreover, initiatives to establish pipeline projects with a high-capacity backbone are maturing. Thus far, the Alberta Carbon Trunk Line is an example of such an open access multi-user infrastructure project with a capacity potential of 14.6 Mtpa. In the United States, the Denbury (now Exxon Mobile) Green Pipeline has the capacity of transporting 16 Mtpa of CO_2 from industrial and natural sources to EOR fields and to permanent geological storage[12]. More information on existing CO_2 infrastructure can be found in Section 2. For emerging projects, the CarbonNet project in Australia plans to build a pipeline which will enable multiple users to store CO_2 up to a total capacity of 6 Mtpa. CarbonNet is foreseen to be operational by the end of this decade[13]. Another relatively mature backbone-based project is the Dutch project Aramis which plans to construct an open access trunkline operating at high pressure that connects the Port of Rotterdam to offshore depleted gas fields in the Dutch North Sea. Although Aramis' first operational phase will handle 7.5 Mtpa, the trunkline is sized to accommodate 22 Mtpa. Aramis is expecting to be online in 2028[14].

It is likely CO_2 will be transported through different modalities. Recently, the world's first cross-border movement of CO_2 for permanent storage was successfully undertaken between a Belgian INEOS production site and the Danish Greensand storage project[15]. Another successful demonstration of a multi-modal value chain for CO_2 is the demonstration project DemoUpCARMA, led by ETH Zürich. As a part of this project, CO_2 has been transported by truck, rail and ship from Switzerland to Iceland for permanent storage in basalt formations through the storage project CarbFix[16].

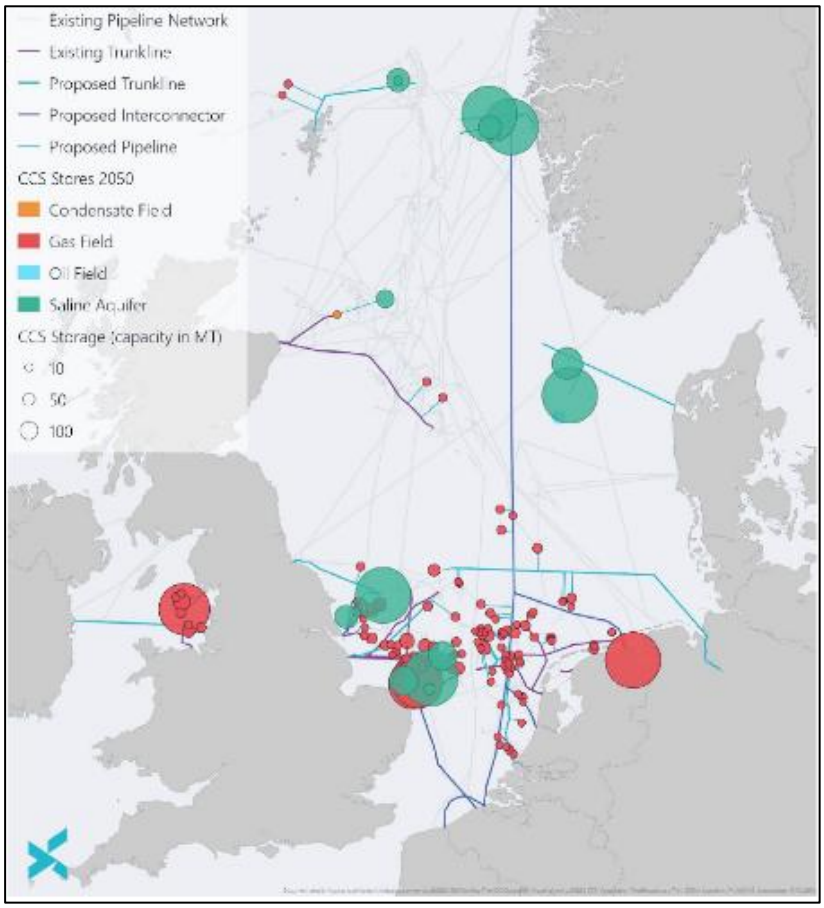

Figure 2. A scenario of CO_2 infrastructure in the North Sea area in 2050 where the need for 100 storage sites is anticipated to accommodate market demand[7].

1.2 (Un)availability of a T&S system

The availability of a T&S system is crucial for CO_2 emitters to avoid venting CO_2 to the atmosphere or interruption to industrial production processes if the T&S system is unavailable. Availability refers to the readiness of a T&S system to receive and handle CO_2 over a given period. To determine suitable or expected availability of a CO_2 T&S network, required or anticipated downtime must be considered. Downtime, both planned and unplanned, can occur along the entire CCS chain, from the production process and CO_2 capture at the site of the emitter, to the elements that make up the transport network and the injection wells. Downtime at one individual element of the chain may have knock-on effects on other parts of the CCS chain. While plannable downtime can be coordinated along the chain to minimise its effect on the availability of a CCS system, other factors may be unplanned. Altogether, the Dutch project Porthos aims to offer a system with an availability between 90 and 95%, accounting for both planned and unplanned downtime of the T&S system[17]. The offshore CO_2 storage project L4a, operated by TotalEnergies and associated with the Aramis infrastructure in the Netherlands (see Section 2), has set a design target for the post ramp-up availability rate of the storage system at 97%[18]. An overview of both planned and unplanned activities that may affect CO_2 T&S networks is discussed below.

Planned emitter outages

Supply of CO_2 to a T&S network could be affected by planned stops at the emitter which can lead to less or no CO_2 either being produced or captured. Planned stops are often required for maintenance and upgrades to production facilities. The frequency and lengths will differ depending on the type of production process. Where cement and ammonia production may pause for a few weeks at a time, steel and aluminium plants often do not stop production during maintenance[19]. Emitters may also produce CO_2 at a variable rate and/or purity, that could impact the T&S operations. These variations in CO_2 supply are further discussed in Section 1.3.

Planned inspection and maintenance to the T&S system

Within the T&S system, the pipeline will need regular inspection and maintenance. For the Dutch project Porthos, maintenance at a pipeline system will include inspection (e.g. magnetic flux inspection for corrosion and metal loss) and liquid removal (e.g. foam pigging) and is planned to be performed during operations[17]. Gassco[20] and Equinor[21] have confirmed that there are very few planned stops in the operation of a CO_2 pipeline. Both hot tapping (making connections to a pipeline in operation) and inspections/maintenance will be performed with CO_2 in the pipeline and during operation. If any larger stops are required, for instance due to pipeline ruptures, the CO_2 would need to be rerouted in order to continue operations during downtime in the affected segment. The compressor will also need maintenance based on its operating hours, but in the Porthos project, compression capacity is designed for redundancy. Planned downtime at the Porthos injection wells consists of SSSV (subsurface safety valve) tests in combination with function tests of the Christmas tree (yearly) and periodically conducting well integrity logs for all (injection and monitoring) wells.

Unplanned outages

It is important to recognise that many developments in current CCS projects, like the Porthos project in The Netherlands, are novel in scale, complexity or reservoir conditions that are being dealt with. In 2023, projects amounting to between 100 and 150 Mtpa of storage capacity globally were in early development phase[1]. Projects will have maintenance plans which aim for optimal availability while

safeguarding their process, but unplanned downtime is inherently unpredictable. Projects will have to conduct appropriate monitoring in order to establish whether all elements of the T&S network behave as designed for as non-conformance may lead to subsequent unplanned downtime of the system. For example, the observation of corrosion during routine monitoring in pipelines or well casings may, in severe cases, lead to downtime for repairs. On the other end of the CCS chain, unplanned downtime at the emitter plant or CO_2 capturing installation may be the consequence of circumstances such as technical failures, staffing issues or market dynamics such as fluctuations in product demand (e.g. energy plants) or supply chain disruptions. Variability of CO_2 streams is an important factor in the availability of a transport and storage network. Section 1.3 provides insight into of variability of CO_2 (and the associated risks posed to the availability T&S system.

1.3 Variability in a CO_2 Transport and Storage system

Variability of CO_2 streams can, in this context, take two forms: variability in composition and variability in supply rate. In order to minimise the chance of downtime, T&S systems that carry CO_2 will have to be sufficiently flexible to accommodate for at least some variation of both types.

1.3.1 Variability in CO_2 composition

Each CO_2 source will produce streams with somewhat different levels of impurities, depending on the type of industrial point source and the capture technology used. The most common CO_2 separation technique is post-combustion capture using amine scrubbing which can produce very similar streams irrespective of the flue gas composition[22]. The presence of impurities (such as water, oxygen, nitrogen, sulphur oxides and many others) in the injected CO_2 stream will likely influence the phase behaviour of CO_2 which, in turn, may impact operation of the pipeline and injection wells. For example, the combination of CO_2 and water can lead to the formation of hydrates at low temperatures, which are solid structures capable of clogging pipelines, wells or the near-well zone of the reservoir. Introducing contaminants allows hydrates to form at relatively higher temperatures[23]. Also, high pressure CO_2 can lead to high corrosion rates in combination with water present, as CO_2 dissolved in water may form carbonic acids which can corrode a pipeline at a rate of 1-2 mm every 2 weeks[22]. However, research and practice has shown that pure CO_2 with a water content below the saturation limit does not pose a risk of corrosion at normal pipeline operating conditions.

A large variability in composition of the supplied CO_2 can be a risk factor in the availability of the T&S network. In order to minimise the risk of injectivity issues or material corrosion as a result of contaminants present, operators of T&S networks may dictate strict CO_2-stream specifications, which allow for limited contaminants in the CO_2-stream. For all networks, these requirements are likely be set before CO_2 is accepted by the network and measured continuously during operations. Off-specification CO_2 is best managed before entering the main network. At the custody transfer point between emitter and network operator, there are shutdown valves which close when off-specification CO_2 is detected. In the T&S network downstream of the emitter, it is important to monitor the composition of the CO_2 and, for example, the corresponding water dewpoint. When free water gets into the network it can be difficult to remove. In such a case, a tracking model can be used to trace the free water in the pipeline and aim to calculate the re-evaporation. This tracking model can be coupled to a predictive corrosion model[24].

Network operators for the Porthos, Aramis and Northern Lights projects have all published their CO_2-specifications. Also, the UK Department for Energy Security and Net Zero has published CO_2-specifications in their consultation for the proposed Heads of Terms for the CCS Network Code[25]. The Porthos contract puts an availability of the composition inlet measurements on 99%[26]. Suppliers of CO_2 that do not meet these specifications risk activating a safeguarding process and may in some cases be

(temporarily) shut off from the network, depending on the risks associated with the breach of protocol. Besides obvious implications to the shut-off CO_2 supplier(s), this may also affect the entire T&S system in the case that the required minimum flow rates now cannot be met. The CO_2 specifications should strike a balance by being stringent enough to prevent any adverse effects to infrastructure but also not overly restrictive to prevent CO_2 suppliers from joining the project because of additional risks or costs.

Standardisation by finding a (international) consensus on CO_2 composition that is deemed safe for transport (in different modalities) and permanent geological storage, is a key enabler for T&S system availability. Currently, CO_2 composition requirements are managed through either commercial agreements or existing regulatory requirements in countries. Such standardisation initiatives have previously been undertaken, on different subtopics, many of them on CO_2 purity requirements. International organisations, most notably ISO, as well as governmental bodies have come up with guidelines for CO_2 capture, transport or storage. Table 1 shows a non-exhaustive overview of previous standardisation initiatives. Currently in Europe, a Technical Committee is established under the European Committee for Standardization (CEN/TC 474) to supplement ISO/TC 265 European standards for not only CO_2 compositions, but for the full life-cycle of a CCUS project, including design, (de)commissioning, construction, operations; inspection and maintenance; safety and environmental aspects; risk and integrity management; monitoring, measurement and verification (MMV) and quantification and finally, carbon accounting across the CCUS value chain[27].

Table 1. Non-exhaustive overview of previously undertaken standardization initiatives.

Authority	Title
International Organization for Standardization (ISO)[a]	Technical Committee 265: Carbon dioxide capture, transportation, and geological storage
Department of Climate Change, Energy, the Environment and Water[28]	Interim National Action List for offshore carbon dioxide sequestration
Department for Energy Security and Net Zero[25,b]	Draft CCS Network Code Heads of Terms (currently still under consultation)
DVGW – Deutscher Verein des Gas- und Wasserfaches [29]	C260- Properties of carbon dioxide and carbon dioxide flow
DNV[30]	Recommended practice: Design and operation of CO_2 pipelines
CarbonNet[31]	Development of a CO_2 specification for a CCS hub network
National Physical Laboratory[32]	Purity Requirements of Carbon Dioxide for Carbon Capture and Storage
Chinese Society for Environmental Sciences[33]	Terms of carbon dioxide capture, utilization and storage (CCUS)

[a] ISO has published 13 standard under this Technical Committee, with 8 currently under development. An overview is available at: https://www.iso.org/committee/648607.html
[b] Currently under consultation.

1.3.2. Variability in CO_2 supply

One of the challenges to the operation of a CO_2 transport and storage network is managing variability or intermittency of CO_2 supply. Although some variability in supply will likely occur, stability of supply is likely to be different from emitter to emitter, depending on the type of industrial process and the market demand for the product. For example, gas-fired power plants, known as swing producers or peaking plants, can be turned on and off quickly (tens of minutes), responding to market demand and therefore may yield variable CO_2 flows. Day-to-day variations in the supply of CO_2 from a power station can range by a factor of 2 to 4, based on the power load variation in electricity grids[22] or based on future scenarios where power production with CCS is used as a load-following grid balancer. On a yearly basis, seasonal variations are smaller, typically by up to a factor of 20-30%[22].

Some industries have seasonal variation in their production processes, such as the increased demand for power for heating in winter. Other industries, such as cement plants, do not run continuously and therefore produce intermittent CO_2 flows. Other industries will typically produce a more stable flow of CO_2 through time, such as ethanol fuel, steel, ammonia and aluminium[19] (Figure 3 gives an example).

A CO_2 transport and storage network is ultimately governed by the needs of injection wells and has to abide by constraints in the system for safe operations. Transport and storage systems have limited operational windows in terms of temperature in wells (to avoid freezing of the annulus fluids in the well, downhole hydrate formation, salt precipitation, thermal cracking), pressure (to avoid two-phase flow in pipelines or wells, or pressure limits related to reservoir and caprock integrity) or flow rates (to avoid erosion and vibration in wells)[34,35,23]. Therefore, intermittency or variability of CO_2 supply through time can in some cases have an adverse effect on the availability of T&S networks.

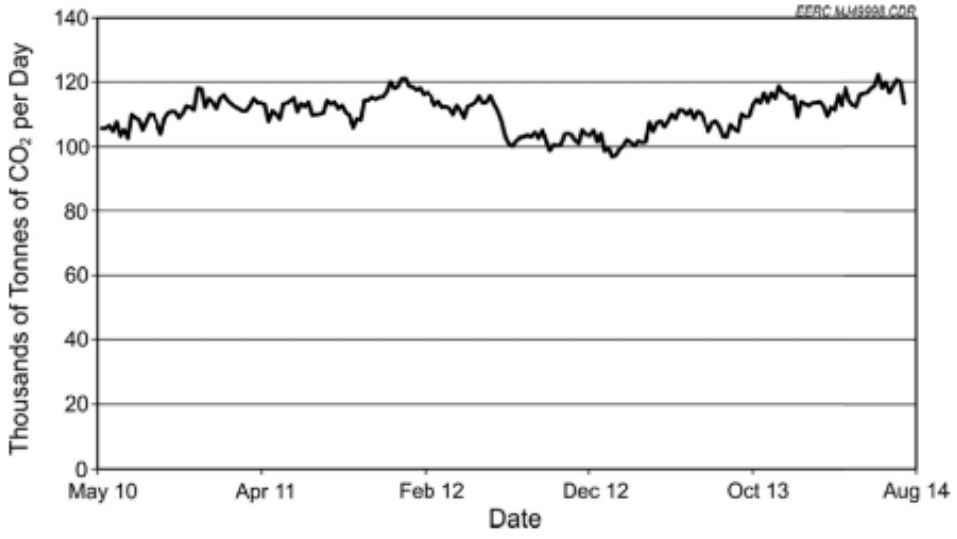

Figure 3. Variability in weekly CO_2 emissions from the production of ethanol fuel in the United States in 2014[22].

The challenge for CO_2 networks is to design a system with an operational envelope as large as possible within the constraints dictated by storage reservoir conditions (i.e. to be as resilient to fluctuations in CO_2 supply as possible). System configuration is an important factor in a system's vulnerability to unstable CO_2 supply. Larger and more complex networks will likely be more resilient to fluctuations in CO_2 from an individual emitter, as well as to upsets at a single well or injection site. A one-dimensional connection from a single supplier to a single storage location will in theory, be more vulnerable to

intermittent or fluctuating CO_2 supply. Designing for a system with terminals and multiple sources and storage sites with a possibility for overcapacity makes the system more robust and flexible. However, the costs for over-sizing infrastructure are potentially high. Also, a complex system will likely require more extensive monitoring and supervision to maintain and optimise its operation.

Variable flow can lead to underutilisation of installed capacity which subsequently allows pressure drops and temperature variations. These can affect materials in the system and potentially lead to thermal fatigue or cracking[30]. On the other hand, oversupply of CO_2 may require CO_2 to be rerouted in order to continue operations. Both issues may affect the overall performance of the system and should ideally be avoided. Depending on design parameters of the T&S network, variable flow of CO_2 (order of hours) may be managed through added flexibility to the system. This could be through buffering techniques such as linepacking, depending on the operating pressure in the pipeline. Alternatively, flexibility can also be built into the system with a buffer of CO_2 in intermediate storage (e.g. small tanks); yet analysis shows associated costs will likely rapidly outweigh the benefits of increased flexibility[19]. More information on buffering is provided in Section 3.

If supply flow rates drop, a buffer or a shut-in will likely be required within a matter of hours to prevent wellhead and bottomhole temperatures from becoming too low. During longer periods of disruptions, when the level of CO_2 supply remains incompatible with the operational window for safe operation after buffers are exhausted, the system will require wells to be shut-in leading to subsequent unavailability of the entire T&S system[36], until CO_2 supply rates return to sufficient levels. In the case of a well shut-in, the pipeline is shut with valves and left with CO_2 inside. Frequent or prolonged shut-in periods can have detrimental effects on reservoir injectivity and the performance of a well. In the case of a transport system that operates at elevated temperatures compared to the ambient temperature, prolonged shut-in may lead to a reduction in temperature and pressure in the top part of the well or the transport pipelines. Subsequently, this temperature reduction may lead to two-phase flow and conditions within the hydrate formation envelope. Although these effects can, for a large part, be mitigated through design choices, stability of CO_2 injection conditions remains important to safeguard injection wells from the aforementioned possible detrimental effects of shut-in periods[22].

Supply variability is fundamentally different when comparing CO_2 transport to natural gas transport, mainly because the movement of product along the value chain is in the opposite direction. For transport and storage of CO_2, there is only a need for CO_2 to be handled if the source is producing CO_2, the injection and storage does not require operation if no CO_2 is available. Only if the CO_2 is used in a production process or for EOR purposes, do the needs of the receiver in terms of the inflow of CO_2, need to be considered when designing the network[37]. This is fundamentally different to networks for natural gas transport, where the production of natural gas needs to be as predictable as possible to meet the demand. For example, Gassco has an extended pipeline network for natural gas, flexible enough to secure gas deliveries to the customers and also ensure that the wells can produce the planned volumes. Having more than one source to produce from provides flexibility to reduce the risk of not being able to deliver natural gas to the customer and also be able to continue production if any customer is out of operation[38]. Section 2 provides further overview of existing CO_2 networks, as well as networks for other gases that can serve as analogues.

2. Existing CO_2 networks and analogues

This section of the report describes the existing CO_2 infrastructure currently in operation as well as outlining existing infrastructure for other gases such as acid gas and hydrogen. There is not significantly public data available of current operational time and maintenance time of the pipelines available and unfortunately lack of this data makes it difficult to give an overview of the achieved availability rates.

Gas transportation infrastructure exists across the world, particularly infrastructure for natural gas since it is a key source of energy for household, transport and industry. In particular, pipelines have been crucial to transport natural gas from fields to terminals and end-users. As a result, large networks for natural gas have been established both onshore and offshore.

In comparison, there are only about 26 commercial CO_2 storage facilities are in operation globally today, with a capacity of approximately 40 Mtpa CO_2[1]. Those CCS networks that are in operation are primarily to transport CO_2 to oil/gas reservoirs for enhanced oil recovery (EOR). To support this, there are currently about 50 CO_2 pipelines, extending over 8000 km, operating in the US which transport nearly 70 Mtpa of CO_2. In Europe, the only existing offshore pipeline in operation is about 143 km long and transports 700 ktpa CO_2 from Melkøya in Norway to the Snøhvit site[2]. CO_2 is also currently used at a smaller scale in the food and beverage industry as well as in the chemical industry, where transportation of CO_2 by trucks and trains is common. Some CO_2 has been transported by ship in these sectors, but with relatively small ships (1800-3000 t) compared to the ones needed for industrial scale CCS. The next section provides more detail on the existing CO_2 transportation network and highlights some new projects under development.

2.1 Existing CO_2 infrastructure

This chapter gives an overview of the existing CO_2 infrastructure and some insights about pipelines in operation with other gases to show the prevalence of such pipelines. An effort has been made to find the operational time and maintenance schedule, but these data are difficult to find in open sources.

2.1.1. USA

As of recent assessments, the United States hosts the most extensive network of CO_2 pipelines globally, spanning approximately 8.370 km (5.200 miles) and transporting around 70 Mtpa[3,4]. These pipelines primarily support EOR operations but are increasingly being considered for CCS projects associated with emissions reduction. See Figure 4 for a map of US pipelines.

The current CO_2 pipeline infrastructure in the United States includes several key pipelines operated by major energy companies (see Table 6, Appendix) and is showed in the map below[5]:

The map shows the footprint of carbon dioxide pipelines in the US. Red lines indicate completed pipelines currently in operation. Blue lines indicate pipelines under development or consideration.

Many of these pipelines transport CO_2 from natural sources for EOR purposes and have been in operation for several decades. However, there is limited information in the public domain regarding maintenance stops or operational time for these operational pipelines. Pipelines have in general very high operational time, and shutdowns are often due to changes in the supply or at the receiving units. There have been some accidents with pipelines that have led to stops/rupture of the pipelines, and an overview of these failures are described in[6].

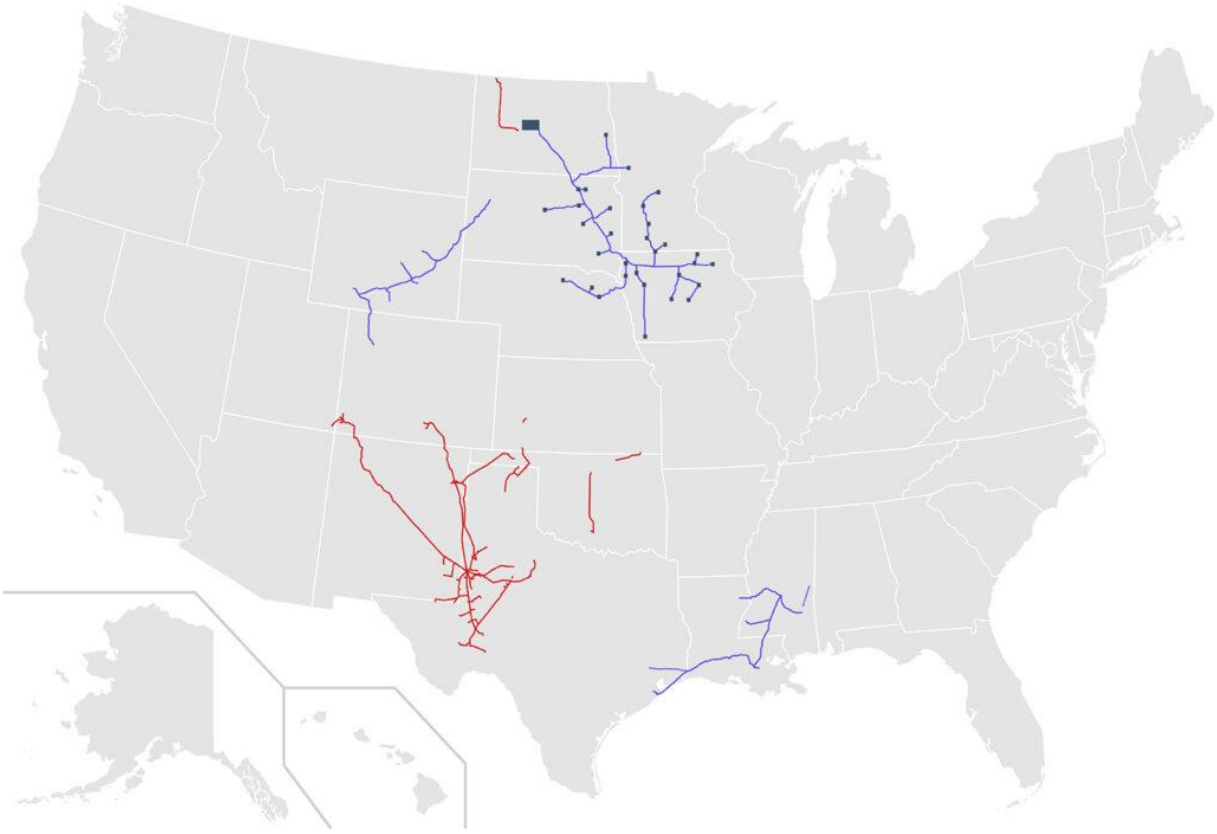

Figure 4 CO_2 Pipelines in US

Since 2021, four major CO_2 pipeline projects have been proposed in the Midwest, aiming to add over 6000 km of CO_2 pipelines, involving both new construction and a conversion[7]. These include Summit Carbon Solutions' 3,200 km pipeline across five states, Navigator CO_2 Ventures' 2,000 km Heartland Greenway project, Wolf Carbon Solutions' 450 km pipeline[8], and Tallgrass Energy's conversion of 630 km of natural gas pipeline to CO_2 transport. However, some of these projects face significant public opposition and regulatory hurdles, such as permit denials in North Dakota, South Dakota, and Illinois, leading to cancellations or suspensions of some planned projects[9]. The Satartia, Mississippi CO_2 pipeline accident is often referred to during public engagement, where a CO_2 vapor cloud was released to the atmosphere after a CO_2 pipeline ruptured due to a landslide[10]. These challenges highlight potential roadblocks in the expansion of CO_2 pipelines, for example on October 20, 2023, Navigator announced the cancellation of the entire project[11].

2.1.2 Canada

Canada's CO_2 pipeline network (see Table 7, Appendix) plays an important role in CCS operations, transporting CO_2 from industrial sources to storage sites. The existing network includes five major CO_2 pipeline systems with a total capacity of approximately 7.1 Mtpa CO_2[12,c].

One of the most notable pipelines is the Souris Valley Pipeline, operated by Whitecap Resources. This pipeline, operational since 2000, stretches 61 km from the Canada-U.S. border near Beulah (ND) to Weyburn (Saskatchewan). It has a capacity of transporting 3.0 Mtpa CO_2 and is primarily used for EOR[2,13]. Another significant pipeline is the Midale CO_2 Pipeline, operated by Cardinal Resources Ltd. This 25 km

[c] An interactive map is available at https://www.cer-rec.gc.ca/en/safety-environment/industry-performance/interactive-pipeline/index.html.

pipeline, located near Weyburn (Saskatchewan), has a capacity of 0.3 Mtpa CO_2 and has been in operation since 2005. Like the Souris Valley Pipeline, it is used for EOR.

The Boundary Dam to Weyburn CO_2 Pipeline is another important component of Canada's CO_2 pipeline network. Operated jointly by SaskPower and Whitecap Resources, this 74 km pipeline has been operational since 2014. It transports 1.0 Mtpa CO_2 from the Boundary Dam Power Plant (Saskatchewan) to the Weyburn oil fields for EOR purposes. This pipeline underscores the integration of power generation and CO_2 transport infrastructure, enabling the effective use of captured CO_2 for EOR.

Shell Canada operates the Quest Pipeline, a part of Alberta's CO_2 infrastructure. The 64 km pipeline, which has been operational since 2015, transports 1.2 Mtpa CO_2 per year from the Scotford Upgrader to storage wells near Thorhild (Alberta). Unlike the other pipelines mentioned, the Quest Pipeline is primarily used for permanent storage[14].

The Alberta Carbon Trunk Line (ACTL), operated by Wolf Midstream, spans 240 km from Sturgeon County to EOR operations near Lacombe (Alberta). This pipeline has an initial capacity of 1.6 Mtpa CO_2, with potential expansion up to 14.6 Mtpa[15]. It has been operational since 2020[16].

It has also been suggested that salt caverns could be a cost-effective solution at capture facilities in Alberta in the event of pipeline outages or reduced throughput to provide temporary surge storage within the pipeline system[17].

2.1.3 Norway

Norway currently has two operational CO_2 storage projects, both of them with the purpose of sweetening produced natural gas (i.e. removing CO_2 from the natural gas to comply with gas sales specifications). At the Sleipner platform, CO_2 is separated from the natural gas and injected through a single well to the storage reservoir. The project has been running since 1996, and stores about 1 Mtpa. The other ongoing CO_2 project is the Snøhvit[2], where CO_2 is separated at the onshore terminal and liquefaction plant at Melkøya in Northern Norway. CO_2 is transported via a 143 km pipeline to an offshore sandstone formation close to the gas reservoir. This project started in 2008 and stores up to 700 ktpa.

The Longship project in Norway is planning to transport CO_2 by ship from industry sources to a terminal at the west coast and then, by a 110 km pipeline to the offshore formation (Aurora) for permanent storage. The project will start up in Q3 2025, transporting approximately 400 ktpa in the first phase with several additional phases planned. The pipeline from the shipping terminal to the storage site is under constructed and has a capacity of 5 Mtpa[18].

In addition to these pipeline projects in Norway, CO_2 is captured at the Yara ammonia plant in Porsgrunn and delivered by truck and/or ship for use in the beer and food industry as well as for technical purposes. For shipping, the CO_2 is transferred in a pipeline from the intermediate storage to the quay and holds a pressure of 15-19 bar and approx.-30 °C. The CO_2 is marketed by Nippon gases[19].

2.1.4 The Netherlands

In the Netherlands, there is a pipeline currently in operation transporting CO_2 for utilization (the OCAP pipeline) and there are also several CCS projects under planning and construction in The Netherlands.

This OCAP CO_2 pipeline[20] supplies CO_2 to greenhouses in The Netherlands and is owned and operated by Linde (Figure 5). According to information kindly given by Jan Willem Veenstra, OCAP asset manager and Karin Ipema, OCAP director, the OCAP pipeline is functioning well. The sources of CO_2 are the Shell refinery in Pernis and the Abengoa Bioenergy bioethanol plant in Rotterdam, providing CO_2 at a gas

composition that is suitable for growing plants in greenhouses. Part of the pipeline was formerly used for crude oil and OCAP has had no technical issue with re-using of this line. Before re-use, the lines were cleaned, and a detailed inspection was done. No new coatings or similar were applied and the CO_2 is dry (less than 40 ppm H_2O). The maximum pressure in the system is 20 bar, and part of the system operates at 8 bar, but 2.5 bar is delivered locally to the greenhouses. The plants in the greenhouses do not require CO_2 when it is dark so the pressure in the main pipeline is reduced during daylight and during darkness the pressure is increased to be ready for CO_2 delivery the next day, enabling the pipeline to act as a buffer store through line-packing. Furthermore, the need for CO_2 is less during the winter months so excess CO_2 is emitted to the air during these times.

There are also two projects in the planning stage of development in The Netherlands, Porthos and Aramis. An earlier project, ROAD, has been discontinued.

Figure 5. OCAP pipeline (in green) with possible extensions (in blue)[21].

Aramis[22] is a project in Rotterdam to provide CO_2 transport for industry emissions to permanent storage via an offshore pipeline to the North Sea. The project aims to capture CO_2 from several industrial facilities and transport the CO_2 to a collection hub on the Maasvlakte (CO2Next), either with onshore pipelines or by ship. At the CO2Next terminal, the CO_2 is compressed and temporarily stored before sending it to storage in an offshore pipeline to a distribution platform, where several wells will be connected. In June 2024, the CO2Next terminal entered the Front-End Engineering Design (FEED) phase, and the final investment decision (FID) is scheduled for 2025. Other components of the Aramis project are also still in the planning phase, and no final investment decisions have yet been taken. The initial launching phase foresees injection of 7.5 Mtpa in the depleted fields K4 (TotalEnergies), K14-FA (Shell) and L10 (Eni Energy Netherlands)

Porthos[23] is another developing project in which CO_2 from industry in the Port of Rotterdam will be transported and stored in empty gas fields beneath the North Sea. The companies will supply their CO_2 to a collective pipeline that runs through the Port of Rotterdam area. The CO_2 will then be pressurised in a compressor station before being transported through an offshore pipeline to a platform in the North Sea, approximately 20 km off the coast. From this platform, the CO_2 will be pumped into an empty gas field. The empty gas fields are situated in a sealed reservoir of porous sandstone, more than 3 km beneath the North Sea. Porthos will store around 37 Mt CO_2, approximately 2.5 Mtpa CO_2 for 15 years. A positive final investment decision for Porthos was taken in October 2023. Construction began in 2024, and the system is expected to be operational in 2026.

The ROAD Project (Rotterdam Opslag en Afvang Demonstratieproject)[24] was one of the leading CCS projects in Europe from 2010-2017, aiming to be one of the largest integrated carbon capture and storage (CCS) projects in the world. The plan was to install carbon capture on a coal-fired power station in Rotterdam and store the CO_2 in an empty off-shore gas-field. The project ran from 2009 to 2017 and was a joint project of Uniper (formerly E. ON) and Engie (formerly Electrabel and GDF Suez). The project was unfortunately called off when the carbon price collapsed in 2012, since the lack of financial support and a business case made it impossible to come to a positive final investment decision. The Road project was further morphed into Porthos[24].

2.1.5 Australia

Australia currently has two operating commercial-scale full-chain capture and storage project (Gorgon CCS, Moomba CCS), one operational research and demonstration project (Otway International Test Centre), and a growing number of commercial-scale projects at various stages of development, both onshore and offshore (Figure 6). These projects propose a combination of existing gas pipeline re-use and new pipeline construction as well as international import facilities.

Chevron Australia's Gorgon liquefied natural gas (LNG) facility[25] is the world's largest CCS system designed to capture carbon emissions to sweeten natural gas, like the two projects in Norway. Naturally occurring CO_2 mixed with the natural gas is produced from offshore gas reservoirs and injected into a giant sandstone formation 2 km beneath Barrow Island (Western Australia), to be permanently stored[26]. A 7 km CO_2 pipeline runs from the LNG plant to the injection wells through highly protected environments. More than 9.5 Mt CO_2 have been injected since startup in August 2019 to June 2024. The startup of the CCS system was later than originally planned to reduce the volume that has been captured so far. Storage have so far not been at planned rates partly related to the need to extract water from the storage reservoir[27].

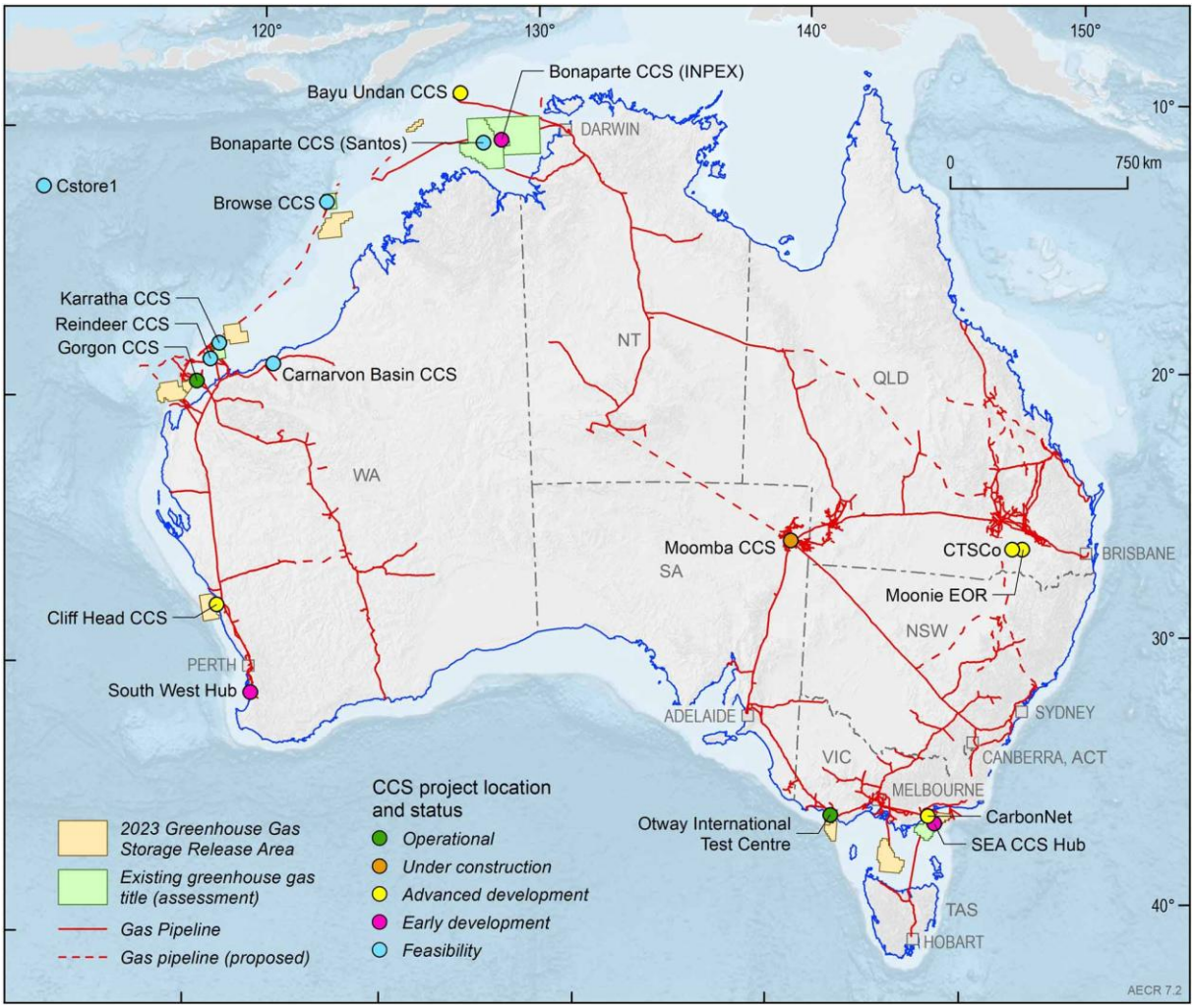

Figure 6 Location of Australian CCS Projects to June 2024. Note that only projects with a geological storage component are included. © Commonwealth of Australia (Geoscience Australia) 2021 , CC BY 4.0

The Moomba CCS project in Australia's Cooper Basin was brought on-line in October 2024 and is now one of the world's largest operating CCS projects, with a potential to store up to 1.7 million tonnes of CO_2 per annum. The project captures CO_2 emissions from the adjacent Moomba Gas Plant and stores them in depleted reservoirs. The 55 km transmission pipeline required a complex specification to ensure it was suitable for sour as well as extremely low temperature service[28].

2.1.6 China

China has experience of operational and recent historical CCS projects, commencing with Enhanced Oil Recovery by CNPC (China National Petroleum Corporation) at Daqing oilfield in 2003, and now with over 100 CCUS demonstration projects in operation or under construction. These range geographically from east, through south Mongolia in the north-west and Xinjiang in the far west. Several of these projects are currently operational pilots, but in total China is capturing about 4 Mtpa CO_2 and storing around 2 Mtpa CO_2. The total length of the existing CO_2 pipelines is about 250 km[29].

In 2021, CNOOC initiated China's first offshore CO_2 storage project in the Enping 15-1 oilfield, located in the Pearl River Mouth Basin. By June 2023, this pilot project became fully operational, with an initial capacity to inject 300 ktpa CO_2, potentially scaling to 1.5 Mtpa. The project uses a "dome-like" geological

structure under the seabed for storage, and it required the construction of one of the largest offshore platforms in Southeast Asia.

2.2 Existing infrastructure for other gases

The design and operation of networks used for other gas systems in the North Sea (e.g., Figure 7) have been studied to derive information about availability rates and best practices regarding downtime of (parts of the) system and methods used to increase system flexibility (such as installing multiple connections between network nodes or constructing ring mains).

Several natural gas networks are in operation in the world today. In this chapter, the natural gas system in Norway is described as an example.

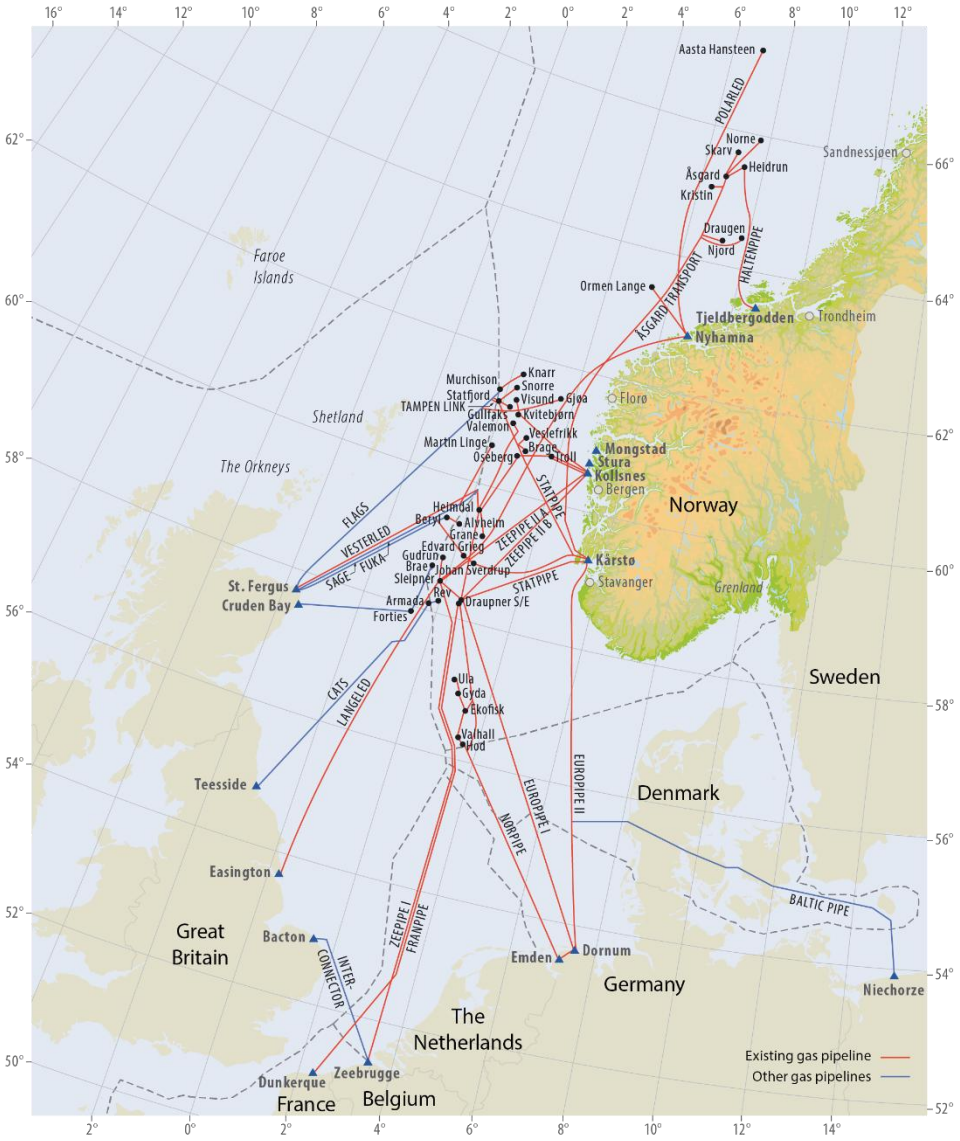

Figure 7. Natural gas network in the North Sea[30].

The natural gas transporting system in Norway gives valuable insights on the importance of flexibility and robustness of such a system. The infrastructure is coordinated by Gassco, and a substantial number

of wells and terminals are linked together. Approximately 8830 km of pipeline are in operation transporting natural gas to 6 different terminals in the UK, France and Germany. A continuous monitoring and modelling system ensure that the customers get the gas they need with the correct composition and also that the wells can produce their planned amount of gas. The system has extra capacity to be able to maintain required deliverables: wells, pipelines and terminals schedule weeks ahead how their needs and capacity is planned. Svein Solvang of Gassco[31] stated that the pipeline has high operational uptime and that most of the maintenance and inspections happen with gas running through the pipelines. In addition, there is on-land gas storage in both UK[32] and in Denmark[33]. There are examples of pipelines being damaged by ankers, e.g. the CATS pipeline in the UK and the suspected sabotage of two pipelines in the Baltic Sea[34]. Danish Authorities concluded the Nord Stream 1 and 2 pipelines had been "sabotaged" in September 2022 but said there was no basis for pursuing a criminal case. Responsibility for the suspected sabotage is still unknown as of Oct 2024[35].

2.2.2 Acid gas pipelines and injection

Another experience that has been examined is acid gas injection. Acid gas is the mixture of varying proportions of hydrogen sulphide (H_2S) and CO_2 that is highly corrosive. Canada has decades of experience in injecting acid gas in saline aquifers and depleted hydrocarbon reservoirs driven by the need to dispose of H_2S produced together with natural gas[36]. It has been considered an analogue for CO_2 injection and storage[37].

2.2.3 Hydrogen pipelines

Over 4,300 kilometres already exists for hydrogen transportation, where over 90% is located in Europe and North America[38]. Currently, 2,575 km of hydrogen pipelines exist in the US today. Several studies[39]look into the possibility of using the natural gas transport system to transport a mixture of natural gas and hydrogen gas mixture.

2.3 Summing up the existing infrastructure findings

There is a lot of experience with and knowledge of gas transport including transportation of CO_2. Even so, finding data for availability and details regarding operation time for existing pipelines is difficult to find. Nevertheless, given the volume of gas pipelines in the world, there are few CO_2 pipelines with the purpose of CCS, but the market is growing. Almost all the existing CO_2 pipelines are in the US, onshore and for CCU purposes. Pipeline transport in general is reliable, has high availability and once built the cost of operation is often low compared to other transport modes. High CAPEX and the lack of flexibility after the pipeline has been built are drawbacks. Combining CO_2 pipelines and terminals in a network provides more flexibility and reduces the risk of unstable delivery and production.

Temporary interruptions to storage and enhanced oil recovery operations may not present significant challenges. However, in the event of pipeline outages or reduced throughput, CO_2 capture operations would potentially need to be halted or CO_2 vented. To ensure continuous CO_2 capture, the integration of temporary local storage at the capture site could be an important element within the CCUS system. This could enable uninterrupted operation even when pipeline capacity is compromised.

2.4 Building robustness and flexibility into CO_2 infrastructure

For CO_2 infrastructure to be developed, a focus on robustness and flexibility is necessary. Reliable distribution for CCS is important both for CO_2 storage and utilization. One way to increase flexibility is to connect a range of transport infrastructure in hubs/terminals. Hubs could combine CO_2 from multiple sources into one or several pipelines or ships. With several sources and sinks linked together, the network may still be able deliver CO_2 to the sinks even if one source has stopped supply, and the sources

may be able to deviate CO_2 to another sink if one sink is temporarily stopped. There will be maintenance needed in both facilities for the production of CO_2 and injection, so the hubs make it possible to keep running the network even if one node is out of operation. In addition, the cost of transport, injection and storage of CO_2 are related to the volume handled, so sharing the infrastructure also reduces the cost per ton transported.

CO_2 transport and storage projects are building flexibility and robustness into the design of their systems through leveraging the hub approach. The Acorn project in the UK is one example with multiple wells and storage possibilities, and another is the Aramis project (Figure 8) that integrates a shipping terminal into its transport system to increase the system's operational envelope and flexibility. In the following, the Aramis project is explored in more detail.

The Aramis project in Rotterdam is designed to connect multiple sources to the pipeline, providing flexibility to pipeline and wells. As the CO_2 in the onshore pipelines is transported in gas phase, the line packing offers an extra buffer. Line packing is a method that uses the pipeline itself as a buffer storage, compensating for fluctuations in the fluid supply or demand. In offshore pipelines, the transport is in liquid phase, and the line packing will not have the same buffering ability. Nevertheless, the pipeline is over-sized compared to the CO_2 to be transported in the first project phase, so some buffer capacity is already in the pipelines. Section 3 contains additional information on linepacking. Having multiple wells may also be a way to reduce the risk of not being able to store the CO_2 if there are any issues with one of the wells. Such extra capacity makes the system very robust and flexible but also is likely to add extra costs.

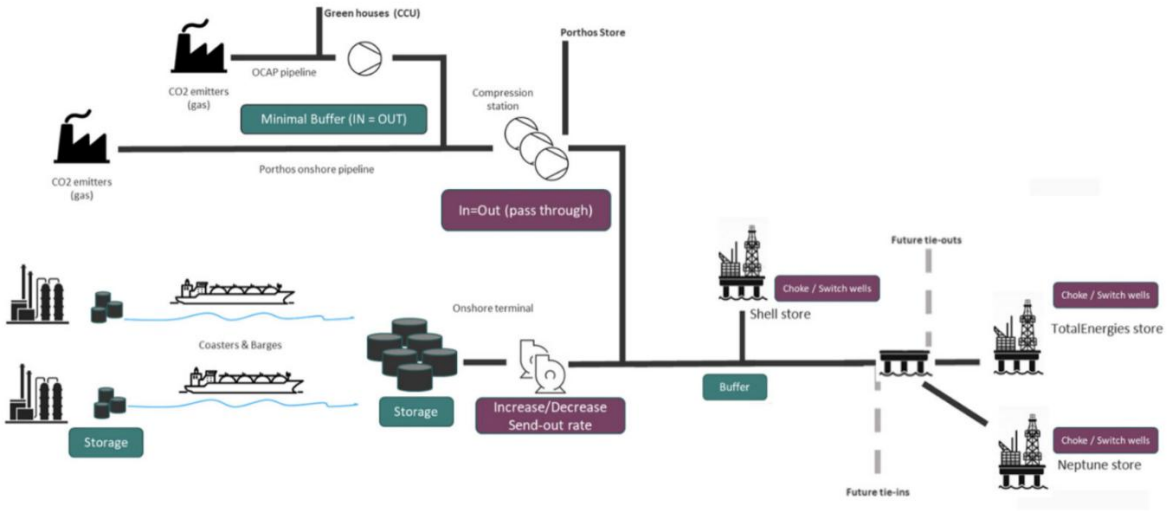

Figure 8. Aramis overview. Note 'buffer' (right centre), representing the buffer capacity of the pipelines, and the buffer capacity of the shipping terminal (centre).

In the case of Aramis, the CO_2 pipeline will be crucial for ensuring the reliability of a CCS network. Since the network serves multiple CO_2 sources, the supply will likely remain stable and less affected by disruptions or planned/unplanned shutdowns of CO_2 generation or capture processes. Similarly, multiple CO_2 injection wells at various locations may help maintain a consistent storage capacity, even if some wells are shut-in or undergoing maintenance.

However, the pipelines will be the main route for transporting CO_2 from capture facilities to storage sites. Any interruptions in pipeline operations, whether for planned maintenance or unexpected events like third-party damage or leaks, could temporarily halt CO_2 transport. While temporary interruptions might

not significantly impact storage and enhanced oil recovery operations, they would require immediate shutdown of capture operations or venting of CO_2 if the pipeline is not functioning, or its capacity is reduced. To ensure continuous CO_2 capture, intermediate storage tanks at the capture site may need to be integrated into the CCS system, allowing capture operations to continue even if the pipeline is unavailable or operating at reduced capacity. These tanks are costly, and it should be considered against the probability for shut down of the pipeline. Pipelines are operating more or less all the time, even during maintenance, and the intermediate storage will only be needed if significant damage should occur.

3. Network flexibility: technical constraints and design options

Large-scale CO_2 transport is expected to be developed in different modalities: trucks, trains, ships and pipelines. However, the major current and planned CO_2 infrastructure consists of pipeline networks. In the design of a transport and storage (T&S) network for CO_2, the requirement is that the system is available as much as reasonably possible. In order to maintain a business case, a T&S network will need to be able to meet the required flow rate targets for longer periods of time, in line with commercial contracts. Downtime will need to be minimised, maintenance coordinated along the chain and expensive interventions like well work-overs avoided where possible.

Moreover, T&S networks will need to be designed with a certain degree of adaptability where it comes to uncertainties regarding, for instance, variations in CO_2 supply. In order to deal with temporal (e.g. seasonal) variability in CO_2 supply, it is important for a storage operator to be able to accommodate a range of flow rates without any gaps in the operational window of the injection site. In addition, it is preferable to avoid unique injection configurations for a given flow rate, such that only one well or one combination of wells are able to accommodate a specific injection rate, but have alternatives available. An important factor in the resilience of a T&S network is redundancy in the system, which is always a trade-off between mitigation of risks vs. costs.

For large-scale cross-border CO_2 transport, minimizing disruptions is critical. Several strategies can help:

- Buffer stores: temporary/intermediate storage facilities that hold CO_2 and can release it during short outages or maintenance, ensuring continuous pipeline operation.
- Line pack reserves: allow for CO_2 to be stored within the pipeline itself, maintaining pressure and minimizing flow disruptions during maintenance or operational challenges.
- Alternative routings: developing secondary routes or alternative pipeline pathways that allow CO_2 to continue flowing if a primary route is temporarily unavailable.

These measures provide resilience and flexibility, ensuring that CO_2 transport remains uninterrupted even during outages or unforeseen events, which is particularly important for large-scale international CCS projects.

This section considers both the constraints project developers have to work with, as a result of reservoir conditions, as well as the options that project developers have to increase the flexibility of transport and storage systems. A large part of this section discusses depleted fields as these tend to be more constrained in their operational envelope as a result of pressure drop in the well and therefore less flexible compared to saline aquifer storage. Finally, this section includes a dynamic response simulation which demonstrates the system's response to temporarily lowered flow at the inlet or to downtime at individual wells. In this section the focus is on the pipeline based CO_2 networks for CCS purposes.

3.1 Constraints for CO_2 injection

Most of the global CO_2 storage portfolio consists of either depleted hydrocarbon (gas) fields or saline aquifer formations. The most notable difference between the two is the fact that depleted gas fields are likely to be significantly below hydrostatic pressure before injection due to years of hydrocarbon production – occasionally they go as low <10 bar (e.g., the HyNet project in the UK)[1]. This Section (3.1) outlines the physical constraints when injecting CO_2 for permanent geological storage, after which Section 3.2 dives into the engineering options to increase a network's flexibility.

3.1.1. Aquifer storage

In contrast to depleted fields, saline aquifers offer storage capacity at or close to hydrostatic pressure meaning the contrast between the conditions at which the CO_2 arrives and the conditions in the reservoir is much smaller, which makes operations in the well more easily managed. However, saline aquifers have different restrictions where it comes to the risk of halite (salt) precipitation around the well, which may lead to injectivity impairment and potentially to downtime at the affected injection wells.

Halite precipitation is the result of the injection of dry supercritical CO_2 into a reservoir with a saline brine. The injected CO_2 interacts with saline brine in the reservoir, causing water molecules to evaporate and diffuse into the CO_2 phase, allowing salts to precipitate and accumulate in the pores in the near-wellbore area[2]. Lab tests conducted on core samples by Edem, et al. (2023)[3] have shown that salt precipitation can have significant impact on both the porosity and permeability, reducing them as much as 6% and 70% respectively, depending on reservoir conditions, brine salinity and CO_2 flow rates. The decline in injectivity due to salt precipitation has been observed in several CO_2 injection projects associated with saline aquifers (e.g. the Snøhvit project)[4].

Mitigation techniques are aimed at maintaining injectivity and desired flow rates, while also preventing damage to the formation. Mitigative strategies include the injection of fresh water, low-salinity water or acids. While the injection of fresh water has proved to be effective in the short term, a rapid decline in injectivity after resuming CO_2 injection suggests salt recrystallisation is likely to occur[2]. Fresh water injection is employed to effectively wash the near-wellbore area of precipitated solids in an attempt to redissolve salt and improve injectivity. However, freshwater injection experiments conducted by Kleinitz, et al. (2003)[5] suggested it would take 3 days to dissolve a 1 mm salt grain and that shut-in periods for freshwater injection are expected to be long (likely in the order of days/weeks), leading to lower availability rates of CO_2 injection operations. Alternatively, salt dissolution in the near-wellbore area can be enhanced by introducing acids such as acetic acid and hydrochloric acid. However, acids are highly corrosive to equipment and may induce geochemical reactions between rock, brine, acid and CO_2, that may affect the geo-mechanical integrity of the reservoir rock[2]. Several other injection strategies have been proposed or tested in laboratory settings. Examples include milling and fracturing, injecting below the critical salinity limit (for which establishing a standardised critical salinity limit has proved challenging since it varies significantly across formations with different geological properties), brine recirculation and the injection of CO_2 microbubbles[2].

Salt precipitation due to CO_2 injection in saline aquifers is a highly complex physical and chemical process which depends for a large part on reservoir characteristics, such as brine salinity, rock mineralogy and pore structure. The influence of flow rates on salt precipitation also depends on reservoir conditions. The selection of mitigation strategies will therefore be highly case-specific, tailored to the reservoir conditions and the chosen injection methods.

In contrast to CO_2 injection in depleted fields, the risk of operating conditions that may lead to two-phase flow or hydrate formation is much lower due to the higher pressures required for CO_2 injection in saline aquifers. Table **2** gives a high-level impression of the differences between CO_2 injection in depleted fields and saline aquifers.

*Table **2**. Some high-level differences (non-exhaustive) between injection into depleted fields vs. aquifers*

	Depleted field	Aquifer
Injection approach	Project-specific design required to handle low reservoir pressure	Relatively more straightforward injection: the fluid in the well is always at high pressure
Two-phase flow	Very likely during project lifetime	Reservoir, well and pipeline at high pressure: risk is low
Salt deposition	Risk depends on reservoir properties	Real risk, requires mitigation measures
Hydrate formation	Possible, depends on reservoir properties	Low risk due to high pressure in system

3.1.2. Depleted fields

Injection of CO_2 into depleted fields poses challenges due to lower reservoir pressure at the start of injection compared to a saline aquifer at near-hydrostatic pressure. A wide range of pressure conditions can be found in depleted fields, typically in the range of approximately 5-50 bar[6]. Reservoir conditions determine the restrictions on temperature (for instance to avoid freezing of the annulus fluids and the subsurface safety valves at the wellhead; to avoid downhole hydrate formation), flow (e.g. vibration and erosion of the pipe and tubing), and pressure (e.g. bottomhole, in the transport pipeline, in the near-well zone of the reservoir) in the well which, in turn determine the operational envelope in terms of minimum and maximum flow rate. Although this window can be engineered to a certain degree, the flexibility of an individual well when handling variable CO_2 supply is for a large part a result of reservoir conditions.

In the case of a depleted field, the pressure drop in the well that results from the pressure difference between transport pipeline and reservoir, can lead to low downhole temperatures and conditions that may pose a risk to the integrity of the well (due to material failure, thermal fracturing of the caprock or reservoir) or to the injectivity of the well (reduced due to hydrate formation)[7]. This is illustrated through Figure 9, which shows a simulation of a non-controlled (with pressure control valves that are either fully open or closed) injection well and the relation between the pressure at the wellhead (in blue), the downhole temperature (in red), the mass flow rate and the CO_2 temperature (symbols). In this example, the reservoir is assumed to have a pressure of 20 bar (left) and 100 bar (right). Operational limits are indicated by the two horizontal dashed lines which represent the minimum temperature (in red, at 15°C) at bottomhole, below which hydrates may start to form, and the maximum pressure (in blue, at 120 bar) at the wellhead. The maximum pressure is an assumed limit of the transport system for safety considerations (to prevent leaks and ruptures). In practice, typical maximum allowable pressures are often higher: in the range of approximately 140-200 bar[8].

In the case of the reservoir with a 20 bar pressure (left panel), to avoid a risk of hydrate formation, the flow rate must be either low (in this case, depending on the temperature of the CO_2 at the manifold, below 20-40 kg/s) or very high (above about 70 kg/s). In the case of the reservoir pressure of 100 bar

(right panel), the flow rate can be increased without risk of low downhole temperatures and subsequent hydrate formation. This well has an inherent higher operational flexibility for managing variability in CO_2 supply for it can accommodate a wider range of flow rates for all modelled CO_2 temperatures at the manifold. Moreover, the effect of two-phase flow can be observed in the case of lower reservoir pressure (left panel), where the CO_2 is at the phase line and the required pressure for injection becomes a constant with respect to the flow rate (visible in the flatlining of the blue curves in the left panel for CO_2 temperatures at the manifold of 10 and 20°C).

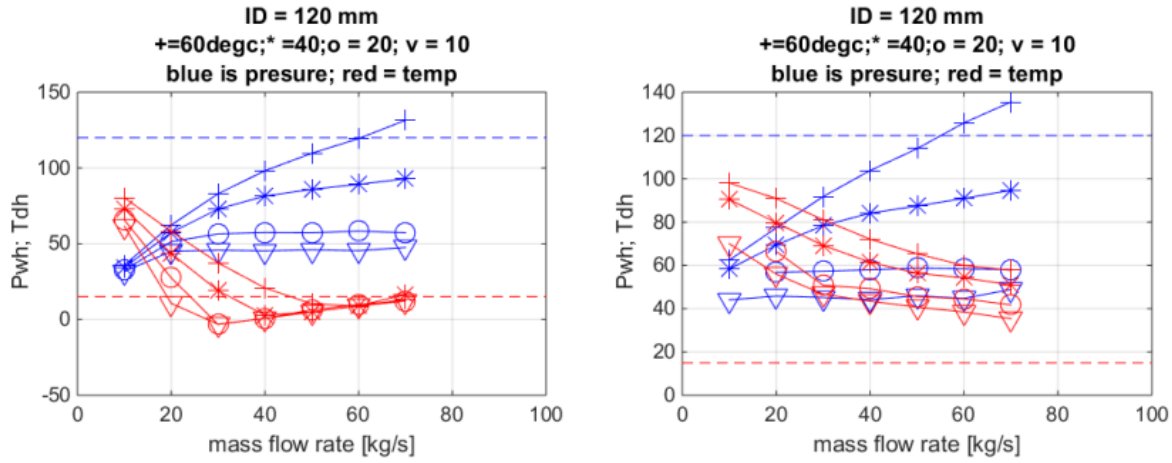

Figure 9. Simulation of wellhead pressure (Pwh; in blue) and downhole temperature (Tdh; in red) as a function of flow rate and CO_2 temperature at the manifold near the wellhead[9] (indicated by the symbols: plus-sign = 60°C, asterisk = 40°C, circle = 20°C and triangle = 10°C). Well design is a vertical monobore with an internal diameter (ID) of 120 mm, true vertical depth of the well (TVD) = 3500m, Thermal resistance (U)=9.5 W/m²K. Left: reservoir pressure 20 bar, productivity index (PI) = $2.53 \cdot 10^{-5}$kg/s/Pa (high-quality well). Right: reservoir pressure 100 bar, PI = $6.14 \cdot 10^{-6}$k/s/Pa. Note: a rate of 30 kg/s corresponds to about 1 Mtpa.

Next to reservoir pressure, another important factor contributing to the downhole conditions during CO_2 injection in a depleted field is the productivity index (PI) of the wells, which is a measure of the ability to produce fluids and is related to reservoir permeability as well as reservoir thickness (assuming injection of CO_2 along the entire reservoir thickness)[7]. High bottomhole pressure and subsequent bottomhole temperature can occur in wells with a poor PI value ("low quality wells" or wells into reservoirs with a lower injectivity). With wells yielding a larger productivity index ("high-quality wells" or wells into reservoirs with a higher injectivity) lower bottomhole pressures and temperatures will occur, possibly exceeding the operational envelope. Depleted reservoirs with low pressure conditions in combination with wells yielding a high productivity are sensitive to cooling effects. An illustration of CO_2 injection in wells with varying PI values is presented in Figure 10. In this example, CO_2 conditions at the manifold are 5°C (temperature of seawater) and 120 bar (transporting dense phase CO_2). The reservoir with the lowest productivity index yields an increasingly higher pressure throughout the well. In contrast, in the reservoirs with higher productivity index (blue and red curves), temperature and pressure remains lower throughout the well and two phase flow can be observed in the top part of the well[7].

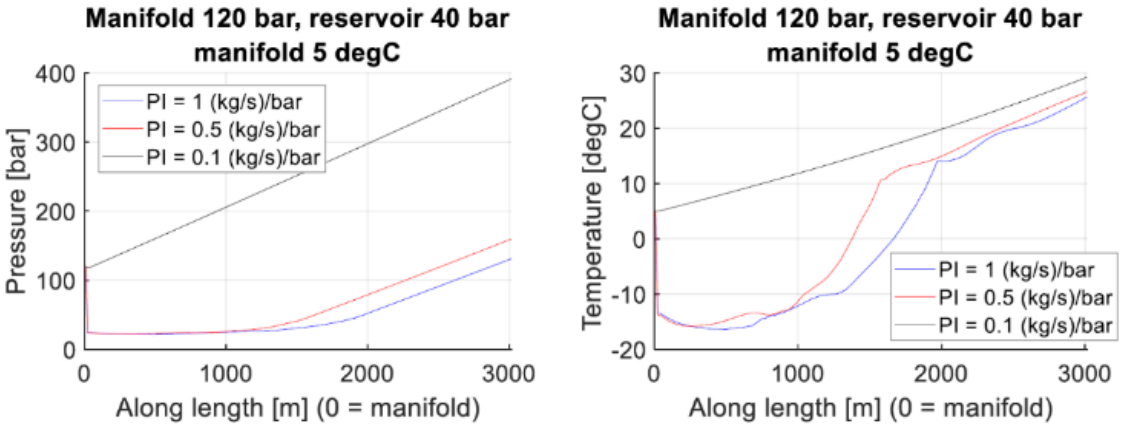

Figure 10. Simulation of pressure and temperature conditions along a CO_2 injection well for three reservoirs with different productivity index (PI) – low, medium and high. PI defined via m [kg/s] = PI ×Dp). A high PI represents a good quality permeable reservoir[7].

Box 1 - Availability of transport and storage with a shipping solution

In addition to pipeline solutions, transporting CO_2 with ships is another option that can be beneficial for emitters that are more isolated and/or further away from pipeline networks. For some emitters, it may be the only economical method of CO_2 transport. Ships can bring CO_2 to onshore collection points (e.g. Northern Lights, CO_2NNECT terminal) or straight to the injection site (e.g. Bifrost). By definition, ships collect and deliver CO_2 in batches, likely leading to intermittent injection, which may pose challenges where it comes to well and reservoir integrity. The advantages of using an onshore collection point include less weather dependent unloading and less equipment on each ship, thereby reducing its costs[10]. The downside is that it does require offshore pipeline infrastructure for the further transportation of CO_2 to the storage site.

Intermittent injection potentially poses risks to well and reservoir integrity. In saline aquifers, low injections rates, which may occur during intermittent injection, can potentially lead to local pressure build-up and subsequent injectivity issues, as a result of salt precipitation close to the injection well[11]. Injectivity issues as a result of intermittent injection can lead to downtime. This has been the case in the Norwegian project Snøhvit, where intermittent injection (as a result of disruptions in CO_2 supply; not due to injection from ships) led to a loss of injectivity due to salt precipitation in the near-wellbore area. Although this issue was temporarily resolved through the use of MEG (a chemical compound typically used to prevent hydrate formation), injection had to be shut down after injectivity issues re-arose shortly after[12].

Ships will most likely transport refrigerated CO_2 of approximately-50^oC[13]. However, when injecting low temperature CO_2 from ships (close to or below freezing point), colder than the ambient reservoir temperature, intermittent injection will lead to temperature fluctuations in the well and reservoir. These temperature fluctuations in the well and reservoir lead to a higher risk of thermal stresses in the tubing and casing, which can affect the sealing abilities of the well (i.e. the casing, cement and rock formation)[10]. The most relevant parameters to temperature fluctuations in the well casing have been identified as temperature of the CO_2 at the inlet, the injection rate, the duration of injection, and the length of the

pauses between injection[10]. Mitigative measures for risks relating to the well and reservoir integrity are conditioning the CO_2 before injecting (e.g. heating the CO_2 using seawater) and designing tailored injection schemes through careful selection of the aforementioned injection parameters (temperature, rate, duration of injection and pauses). The project Bifrost in Denmark is assessing the feasibility of injecting CO_2 continuously from ships, as opposed to batchwise injection[14]. Continuous injection will prevent the temperature fluctuations and the associated risk of thermal stresses in the tubing and casing of the well. In addition, Bifrost is exploring the feasibility of adding operational flexibility through floating CO_2 buffer capacity. Studies into the Bifrost project[14] recommended the addition of a floating buffer capacity of 30,000m^3.

Where it comes to the expected availability of the transportation element, the ships themselves, the Dutch provider of a shipping solutions Carbon Collectors stated that the largest impact on availability rates is expected from weather conditions[15]. Their CO_2 barge-push tug combinations are designed to operate until a significant wave height of 3.5 meters, which should allow for an availability of 95%+, looking at weather conditions alone. The ships are designed for redundancy where possible and economically feasible, such as redundancy in generators and injection pumps. Although injection will be intermittent and some CO_2 may vaporise during periods in between injection, well temperatures are expected to remain manageable regardless of the time between injection periods. Maintenance is planned for the injection system (every 2 years) and for the individual ships (every 5 years).

3.2 CO_2 network design aspects

Current CO_2 transport and storage networks exist in different configurations, each with different operating conditions, future CO_2 transport and storage networks are likely to have an even wider range of operating conditions due to increasingly more complex configurations. These differences, for instance, depend on of the phase in which CO_2 is transported (gas or dense (liquid/supercritical) phase), the location of the network (onshore vs offshore operation), the type of pipeline used (insulated versus non-insulated pipelines), the complexity of the network (single source to single sink, versus more complex networks that link several sources of CO_2 to multiple sinks). As set out in the previous section, CO_2 injection is restricted to an operational window which is for a large part dictated by the reservoir conditions, which can be especially challenging for depleted fields with a (very) low pre-injection reservoir pressure. This section assesses engineering/design options for project developers to build flexibility and resilience into the transport and storage operations by for example increasing the operational window of the wells (well level) or building redundancy in the system (network level).

3.2.1. Network level

This subsection provides an overview of the design aspects, on the level of the T&S network, which can influence the operational flexibility or availability of a CO_2 T&S system.

Network configuration

Today, a number of projects involve a single source – single sink network configuration. An example is the Snøhvit CCS project where CO_2 originates from a single source, in this case the LNG processing facilities near Hammerfest in Northern Norway, and the single geological sink was a single deep saline formation[12]. Generally, a simple CCS chain containing one source and a single storage site is vulnerable to supply variations or injection issues. Unplanned outage along the chain is likely to result in subsequent unavailability of the system.

In other networks, multiple emitters may be supplying to a collection network that feeds into a system with a single storage location. An example is the Porthos network, where four emitters supply to an

onshore collection network, which collectively feeds into the offshore network towards the depleted P18 gas fields. In such a network, capacity management and pressure control of the pipeline is relatively straightforward. The pipeline operating pressure has a lower bound determined by either the minimum pressure to avoid two-phase conditions (including safety margins to account for the shift in the critical pressure due to contaminants in the CO_2) or the minimum pressure required to inject the CO_2 into the wells. To select the optimal operating pressure two factors should be considered: (1) a lower operating pressure directly translates to lower operational costs at the compressor/pump station and (2) the flow needs to be distributed over the wells considering reservoir pressure, injectivity of each well and other reservoir factors (e.g. fault activation).

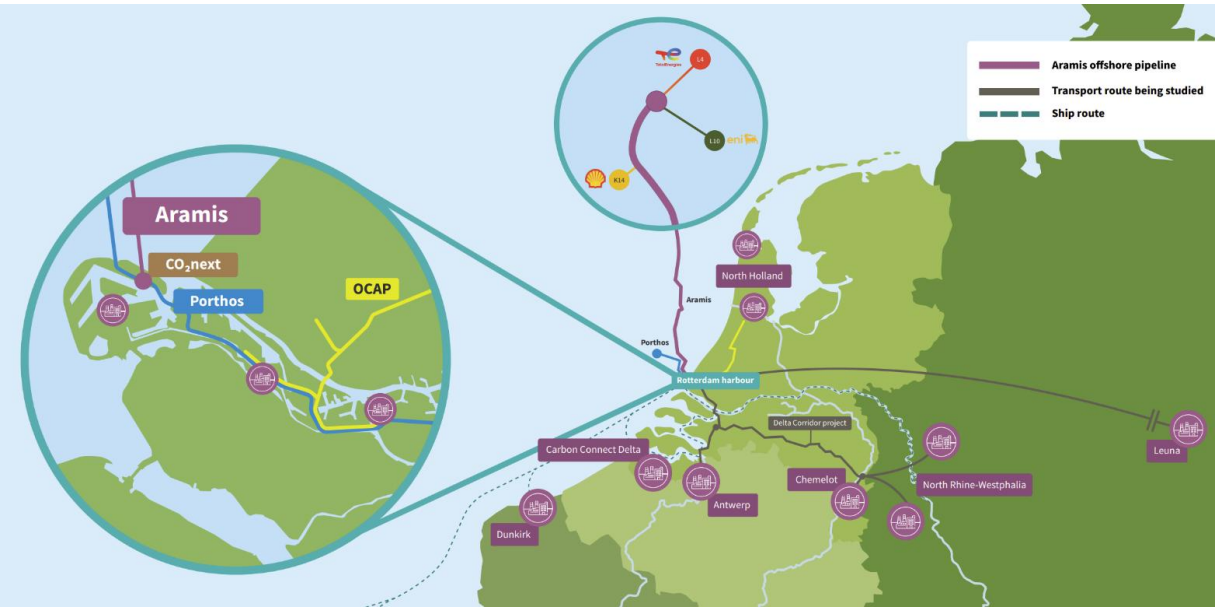

Figure 11. Illustration of the Aramis pipeline for transportation of up to 22 Mtpa CO_2 from the Maasvlakte (Rotterdam Port area) to the three launch stores in the North Sea. Shown in the upper zoom-in panel are the future storage fields of the launching customers of the pipeline: L10 (Eni; in green), K14 (Shell; in yellow) and L4 (TotalEnergies; in red). Also shown, associated infrastructure projects Porthos and CO_2next, the OCAP-pipeline (in the left zoom-in panel) and transport routes being studied, stretching to Belgium and Germany (in brown)[16].

More complex CCS projects follow a hubs and cluster approach, with numerous emitters utilising a single collection network joined with one or more storage locations. There are clear benefits to such an approach including the use of economies of scale and increased flexibility and resilience to unplanned CO_2 supply issues or injection issues at the storage sites. However, finding the right operating conditions for a shared infrastructure connected to multiple storage sites is far less straightforward. Storage operators cannot tailor the transport conditions to the preferred injection strategy at their storage site. For example, it may be the case that transport network pressure needed from a single injection site is detrimental to other injection sites connected to the shared infrastructure. Furthermore, adding a new hub to the network can lead to complications if the new wells cannot be operated at the necessary injection pressure. The topic of shared networks is further investigated in Section 3.3, where dynamic responses of a T&S system are simulated for CO_2 supply rate variations as well as outages at injection sites (wells).

An example of a network using a trunkline to serve both numerous emitters as well as storage operators is the Aramis project in the Netherlands (Figure 11). Aramis intends to build 22 Mtpa trunkline infrastructure to connect the hub on the Maasvlakte, in the Port of Rotterdam area to the offshore

storage sites in the Dutch North Sea. The first phase of operations comprises the launching stores of Shell (K14), TotalEnergies (L4) and ENI (L10), for a total of 7.5 Mtpa.

Gas vs liquid/supercritical phase

CO_2 can be transported through a pipeline network in several phase states, depending on the operating conditions. Generally, dense or supercritical phase transportation is preferred compared to gas phase transportation[17]. Dense or supercritical CO_2 has a higher density and therefore allows larger volumes to be transported in a certain timespan, thus posing a more favourable economic model. Moreover, due to the relatively low density of gaseous CO_2, the pressure in the pipeline may drop significantly and may need re-pressurisation along the transport network[18]. For these reasons, transportation of gaseous CO_2 is mostly seen for relatively short distances and small quantities. For a single gas phase operation, this means a typical maximum pressure of 35 bar, corresponding to a phase line temperature of 0°C. This means that the minimum temperature is 0°C. A typical minimum pressure is 25 bar[19].

CO_2 under supercritical conditions offers a stable single phase for transportation but requires temperature and pressure to be kept above the critical point of 73.8 bar and 31.1°C (for pure CO_2; see Figure 12). Depending on the network conditions and the injection requirements, the pipeline may need to be insulated or the CO_2 may need to be heated to keep CO_2 in a pipeline above the above the critical temperature[18]. This critical pressure increases in case of the presence of contaminants, therefore a typical minimum pressure is 80 bar[19]. This minimum pressure may change depending on the CO_2 composition and the steadiness of the operating conditions. The maximum pressure is determined by the requirements at the injection hubs and by the dynamic behaviour of the network.

Moreover, in order to keep flow conditions stable in the supercritical or dense phase, it is recommended to avoid operating conditions close to the critical point[20]. The temperature and pressure of pure CO_2 in a pipeline at or near the critical point are sensitive to changes in external conditions or operating conditions (pressure and temperature), potentially leading to flow instabilities. For almost all configurations the choice of pressure conditions will be based on the desire for single-phase operation. Therefore, the typical operating pressure is determined by the minimum and maximum temperature expected to avoid two-phase operation. Current project plans assume single phase flow in the pipelines during operation for three reasons: (1) to avoid terrain induced slugging or severe slugging at the flowline/riser at an injection platform, (2) due to large density differences between phases, multi-phase flow may affect the accuracy of flow measurements, which may have implications for compliance to regulations (e.g. ETS)[21], and (3) because of unfamiliarity with two-phase operations.

Recent research[22] showed no hydrodynamic slugging during (near horizontal) flow tests. This is an indication that severe slugging may not occur in practice due to the lower density differences between gaseous CO_2 and liquid CO_2, when compared to gas/water or gas/oil systems[23]. Therefore, two-phase operations might become more common practice than currently assumed once experience is gained with the operation of large-scale transport systems. However, in this report single phase operation is assumed for all pipelines by taking minimum pipeline operating pressures higher than the critical pressure (see Figure 12). In that case, at all temperatures, operation in two-phase conditions are avoided. Maintaining single-phase flow helps ensure predictable behaviour and possibly contributes to the availability of the transport and storage network.

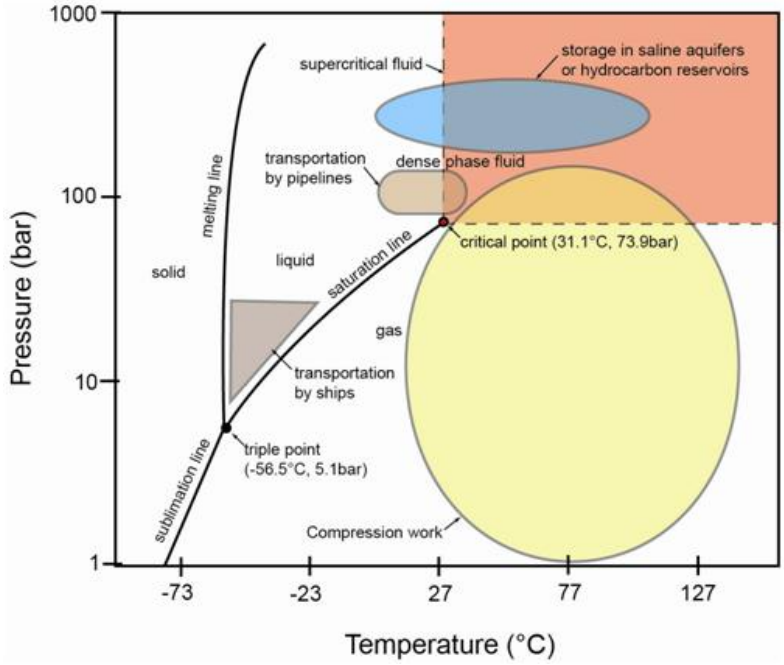

Figure 12 The CO_2 phase diagram showing the pressure and temperature domains for compression, ship and pipeline transportation and storage[24].

Buffer storage

Interim or temporary storage of CO_2 can be incorporated into the design of a T&S system to provide extra flexibility. Buffer storage will be required in intermittent or batch-wise supply chains, for example when CO_2 is shipped. Buffering techniques can also be employed to manage variability of CO_2 supply in pipelines. Quayside storage facilities (storage tanks) will likely be utilised in shipping terminals. An example is the Northern Lights project, which features storage tanks with a capacity of 8250 m^3, which is 110% of the size of a "batch", or one shipload of CO_2 (which is 7500 m^3). Other buffering options include geological storage, either in depleted fields or salt caverns. However, recent research[25] has demonstrated that going beyond buffer storage needed for daily operations, for example, in the case of stalled CO_2 supply in the order of days, is likely to be prohibitively expensive.

Transport pipeline pressure and linepack

Linepack is a term that refers to the total volume of gas stored in a pipeline system. Using the pipeline system as buffering capacity to provide flexibility to the T&S system is unlikely to provide a solution to CO_2 supply fluctuations beyond a few hours. In dense-phase operation, the compressibility of the fluid in the network is low. This means that the network is less suitable to act as buffer or handle flow fluctuations. This is worsened by the temperature influence on density since temperature fluctuations directly result in large pressure fluctuations. The buffer capacity for a dense-phase operation is altogether minimal.

For example, at a temperature of 10°C, the densities at 85 and 120 bar are 908 and 935 kg/m^3, respectively (for pure CO_2). This means the linepacking capacity is minimal – the numbers suggest a difference in mass at 85 and 120 bar of about 3%. The mass to increase the pipeline pressure from 85 to 120 bar is plotted for different pipeline sizes in Figure 13. For a 10" line only 1.4 t/km can be added for linepacking purposes. For a 24" line this is still only 8 t/km. A misbalance between inlet and outlet pressure therefore results in either a pressure increase or decrease. For the latter case of a 24" line, a pipeline with a length of 100 km could buffer about 800 t. If CO_2 is supplied at a rate of 2.5 Mtpa, this

corresponds to about 3 hours of buffer capacity[25]. These numbers agree with the results from earlier studies[26,27].

In gas phase operations, the linepacking capacity in low pressure networks is often higher due to the higher compressibility of gaseous CO_2 in combined with the often large-diameter pipes. This means that gas phase networks can potentially offer greater operational flexibility. However, in practice, even in these networks the capacity is limited by the requirement to keep CO_2 in a single gas-phase, meaning the pressure cannot be increased to a point where phase changes occur. For a low pressure network (25-35 bar), the linepacking potential is approximately 32 kg/m^3 compared to approximately 27 kg/m^3 for a high pressure network (85-120 bar)[25]. Using this number, a low pressure pipeline of 24" with a length of 25km has a buffer capacity of 232 tonnes[25].

Of course, the time in which linepacking can be used to dynamically absorb supply variations is directly dependent on the magnitude of the supply variations. The smaller these variations, the longer the system can accommodate them. Nevertheless, the ability of transport pipelines to absorb supply variations or upsets at storage sites remains very limited.

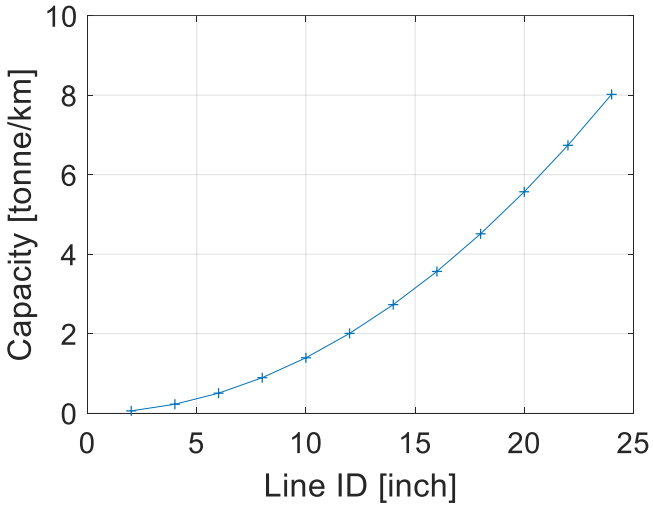

Figure 13. Linepacking for a CO_2 high pressure line (10°C for a pressure rise from 85 to 120 bar)[25].

Onshore/offshore

In contrast to onshore systems, using compressor stations along a pipeline to boost CO_2 pressure to its target pressure, is not viable for offshore CO_2 transport systems. Offshore pipelines tend to operate at high pressure transporting dense-phase CO_2 (the offshore pipeline of Porthos, in the early gaseous project phase, is an exception). In offshore systems, the pressure would need to be high enough along the entirety of the pipeline to ensure single phase flow. Considerations for the design of an offshore pipeline system are the pressure difference between the inlet and the outlet as well as the gravity head gain caused by a potential decrease in elevation, both of which can be engineered through parameters such as pressure at the inlet and the diameter of the pipeline[25].

Besides the differences in flexibility as a result of different linepacking abilities of low pressure gas phase and high pressure phases, as set out in the previous paragraph, the biggest differences between operating offshore and onshore pipeline networks are safety concerns and accessibility of the pipelines

which may influence the availability of a system in the case of malfunctioning of the pipeline (e.g. leakage).

Redundancy in the system

Downtime can potentially be minimized by designing for redundancy in a T&S network. In case of planned or unplanned downtime, operations may not need to slow down or shut down provided sufficient redundancy is built into the network. Along the CCS chain, many components can be designed with spare capacity. For example, redundant injection wells can offer flexibility at one of the critical elements of the system. The Porthos project in The Netherlands has designed spare capacity at the compressor station for redundancy. In theory, even the network configuration can be designed such that multiple pathways lead to an injection site, whereas in a configuration with a single trunkline, downtime will lead to a complete shutdown of the system. Where it comes to redundancy and spare parts, there will always be a trade-off for the critical elements of the system between the chance of them failing, and the costs of installing redundant capacity.

Insulation of pipelines

When injecting CO_2 into depleted wells, temperature is a key parameter. The density of CO_2 is strongly dependent on temperature; hence injection rate varies strongly with varying temperature of CO_2. In addition, there are constraints in the injection strategies related to the wellhead temperature (e.g., to avoid freezing of annulus fluids in the well, or to avoid temperature outside wellhead material specification). Therefore, the temperature of the CO_2 when it arrives at the wellhead is important. A higher arrival temperature means a broader operational envelope for an injection site, for it will counteract the cooling effects that occurs when CO_2 expands into the injection system.

Insulating pipelines will lead to additional costs. Therefore, for long pipelines insulating pipelines may not be feasible. In such a case, the arrival temperature will be equal to the soil or seawater temperature. Insulation of the pipeline infrastructure can be a good solution to add flexibility to a shorter network. The Porthos project in The Netherlands plans to use an insulated pipeline to maintain the elevated temperature of the CO_2 from the heat of the compression process to the well (between 35 and 80^{o}C)[28], thereby extending the operational envelope of the storage system by making use of a higher arrival temperature (see Box 2). Porthos aims to achieve an arrival temperature of 40^{o}C at the wellhead during normal operations[29].

One downside of a system with an insulated pipeline is that long shut-in periods may lead to complex situations, especially for the main transport pipelines in a network (e.g. trunkline). A pipeline that operates with elevated temperature compared to ambient temperature will cool down during a shut-in period, simultaneously decreasing the pressure. This could lead to two-phase conditions in the pipeline. This pressure reduction is greater with higher flowing temperature during operation. In this situation, the presence of contaminants plays an important role because they could increase the chance of two-phase flow. When shutting in a pipeline that operates with elevated temperatures, single phase conditions could be maintained by keeping sufficient pressure in the pipeline during the cooldown. However, this will require available CO_2 to do so (e.g. from intermediate storage of liquid CO_2).

In case of two phases of CO_2 present in the pipeline, restarting operations can be done two ways. First, the pipeline can be pressurized until single phase conditions are reached before opening injections wells. Here, it is especially critical to start the wells in a timely manner, or the low compressibility of liquid CO_2 could lead to pressure spikes in the transport system. Second, injection can be performed at lower pressure, albeit possibly in two-phase conditions. It must be remarked that an extended shut down

period is expected only to occur in case of planned shut-downs, in which case the start-up can also be planned. Altogether, a consequence of two phases in the pipeline might be that the start-up procedure can take longer than for a dry natural gas transport pipeline (order of days)[30]. In that sense, the insulation of pipelines may affect the duration of shut in periods (downtime).

Similarly, this is also the case when depressurization is needed in the network, which may occur during planned operations (e.g. releasing pressure through a valve) or in response/as a result of an emergency situation (e.g. pipe fracture)[31]. During depressurization, low temperatures may occur due to two-phase conditions at lower pressures. Hence, a controlled process of depressurization of (a segment of) a network can take longer to avoid temperature of the CO_2 decreasing beyond the minimum design temperature limit of the pipeline, recovering heat from the surroundings. Again, here exists a strong relation to the flowing temperature of the CO_2 during operations, for warmer CO_2 may shorten this process.

Box 2: Injection window for Porthos

The operational window for CO_2 injection in the Porthos project is shown in Figure **14**. The Porthos project plans injection in 2 depleted fields with a very low starting pressure (order of 15-20 bar). To avoid two-phase flow (which is part of the injection philosophy) as well as hydrate formation, Porthos will start injection in a warm gas phase with a relatively low flow rate during a first commissioning phase. During this phase, the onshore (gas-phase) collection network directly feeds into the offshore line, without compression ('bypass mode' in the figure). Higher rates can be achieved with compression (light blue colors) with CO_2 still in gas phase. When reservoir pressure is sufficiently high, injection will switch to supercritical CO_2 to achieve the targeted higher flow rates of 2.5 Mtpa. Here, lower flow rates may lead to too low temperatures in the well, represented by pink colors in the figure. Liquid injection from the start is theoretically possible but requires a stable and large volume of CO_2 from the start of the operation and results in an inflexible system, where unplanned downtime at the emitter's side may be problematic for the availability of the T&S system.

The Porthos system's operational window shown in the figure is quite complex, requiring careful tuning of transport system pressure and arrival temperature of the CO_2 at the injection platform. The supply of CO_2 from emitters in the Port of Rotterdam is expected to be strongly variable, requiring the Porthos system to be able to accommodate large changes in supply rates. It is the combination of low pressure in the depleted fields (below 20 bar), close proximity to the coast (the location of the compressor) and the expected strong variability of CO_2 supply that resulted in the injection strategy shown in the figure.

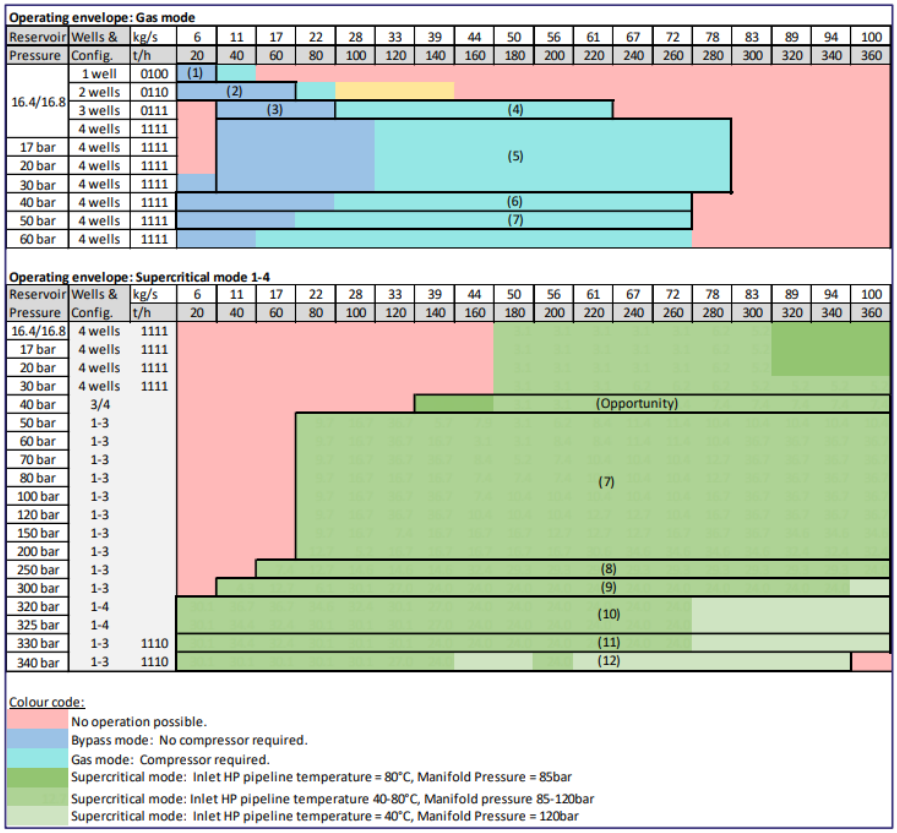

Figure 14. Range of possible flow rates as a function of reservoir pressure for the Porthos project. Top part operation with CO_2 in gas phase; bottom part with CO_2 in supercritical phase. Figure reproduced from the annex to the permit application for reservoir P18-2.

3.2.2. Well level

The flexibility of individual wells in a T&S network has an effect on the overall flexibility of a T&S system. Wells with a broad operating envelope are more likely to accommodate variations in CO_2 supply. Moreover, injection wells may have requirements in terms of temperature, pressure or flow rate which, in turn, may restrict the operating conditions of the transport network. In practice, injection management is especially challenging for CO_2 injection in depleted gas field, which is the primary focus of this subsection.

Tubing size & tapered tubing

In the case of a depleted reservoir with low pressure, the injectivity of the reservoir, temperature of the injected CO_2 and flow rates are important factors in determining conditions at the wellhead and in the injection column in the well. However, this is also influenced by the size of the installed tubing in the well. A well with a smaller internal diameter could maintain CO_2 in a single liquid or dense phase at the wellhead. This is necessary to manage CO_2 expansion effects and to keep the resulting temperatures within the range for safe operations of the materials used. In a liquid or dense phase, the change in temperature of the CO_2 for a given change in pressure is much smaller compared to a situation with two phase flow in the well (liquid-vapour)[32]. Installation of a smaller tubing size could lead to pressure increase at the wellhead which will subsequently lead to higher temperature conditions at the wellhead and the injection column in the well. The choice of a smaller tubing size can prevent subzero temperatures and two-phase flow, however it comes at the cost of decreasing the flow rate of the well since a smaller tubing size will also lead to rapid pressure build-up at the wellhead.

Figure 15 shows a comparison between two wells with different tubing sizes (120mm and 75mm resp.) and the relation between mass flow rate, wellhead pressure and downhole temperature for a reservoir pressure of 20 bar. Figure 15 demonstrates a strong relation between tubing size and pressure build-up at the wellhead (plotted in blue). This pressure build-up will prevent cooling effects due to expansion of CO_2 at the wellhead.

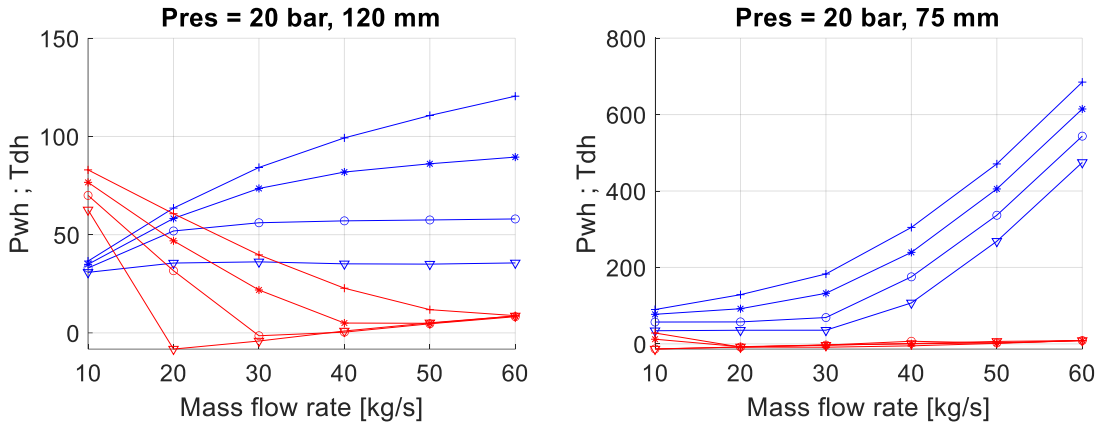

Figure 15. Relation between downhole temperature (Tdh; in red) and pressure at the wellhead (Pwh; in blue), mass flow rate and tubing size of the well (right: 75 mm; left: 120 mm). The well design is identical to the one employed for the simulation in Figure 9. This simulation is performed for this study, following the methodology as outlined in Belfroid, et al. (2021) [9].

Besides small tubing sizes, tapered tubing can also be placed into a well to ensure pressures high enough for single-phase flow in the wellhead and the injection column in the well. The Peterhead Goldeneye (Acorn) CCS project in the UK is an example of a project which intended to use different tubing sizes (4.5" and 3.5") in a well to manage the CO_2 phase behaviour. In this project, considering the arrival temperature of the CO_2, the minimum pressure at the wellhead to avoid two-phase flow was determined

to be 50 bara. The project developer Shell assessed a range of design options for the upper completion of the well to either introduce sufficient friction in the well to keep CO_2 in dense phase (e.g. small tapered tubing, tubing in a dual completion, installation of an insert string, velocity string or concentric strings) or introduce a pressure drop along a device (e.g. installation of downhole chokes). After comparison of factors such as installation ease, reliability, optimisation possibilities, injection flexibility, well integrity, possibilities for in-well monitoring techniques, complexity of well interventions and life cycle costs the installation of a single tapered completion option is presented by the project developer (Shell) as the simplest and most robust solution for this case[32].

Similar to installing a tubing with small internal diameter, a downside of using single tapered tubing is that it limits the range of flow rates due to pressure build-up at the wellhead. In addition, installation of single tapered tubing also imposes a minimum flow rate per well in order to operate the well in single phase. In the case of the Peterhead Goldeneye (Acorn) project, the injection flexibility of the tapered system could be managed through available wells. The full bandwidth of rates from the CO_2 supplier could be accommodated during the life cycle of the well[32].

Downhole chokes

In addition to engineering the tubing of a well such that friction-induced pressure maintains CO_2 in a single phase flow, downhole chokes are devices that can be placed in a well to achieve the same effect. Downhole chokes are devices that are able to manipulate the flow rate of fluid or gas in a well, again at the cost of limiting the flow rates in the well. In the case of a CO_2 injection well, downhole chokes are used to create a pressure drop in the well and thereby maintaining the injected CO_2 in a single phase flow. The pressure drop and the subsequent temperature drop due to the Joules-Thompson effect can be observed in Figure 16. Downhole chokes are often placed at a depth where no phase changes occur, in this case meaning no CO_2 vapour is present, which is often quite deep in the well. For the Peterhead Goldeneye (Acorn) project, project developer Shell performed calculations on a placement of a downhole choke at 1700 m depth along a borehole[32].

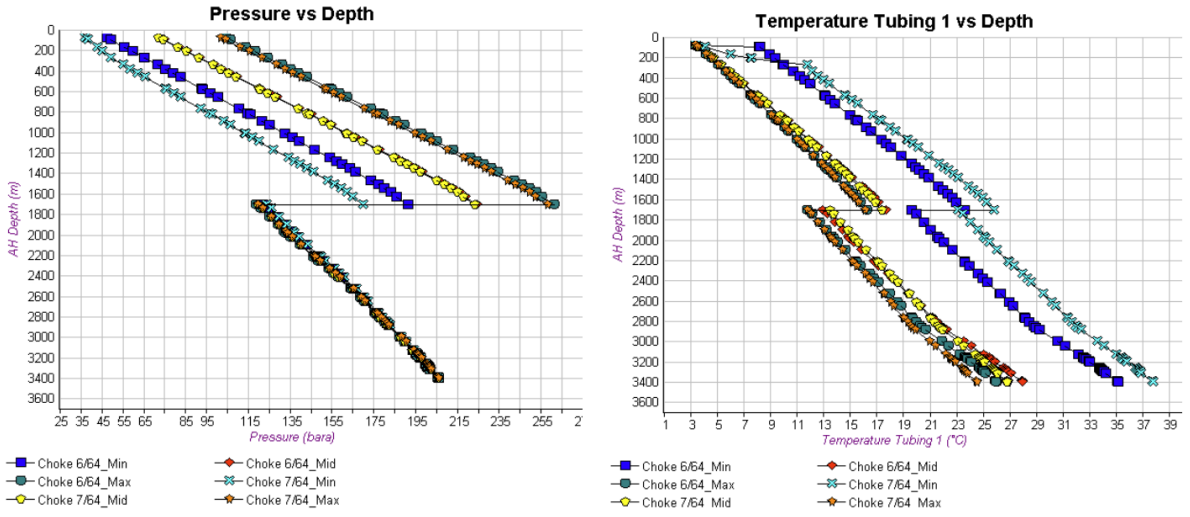

Figure 16. The effect of a downhole choke on the pressure and temperature conditions in a well, from calculations performed by Shell U.K. for the Peterhead Goldeneye (Acorn) project[32]. The graph shows the pressure drop along a downhole choke required to perform injection with a pressure of 207 bara. The different profiles represent two choking devices with a diameters of 6/64" (2.38 mm; denoted as Choke 6/64) and 7/64" (2.78 mm; denoted as Choke 7/64) in combination with different scenarios representative of the operational envelope at the wellhead (pressures between 50 and 115 bara; denoted as scenarios Min, Mid, Max). In this calculation, the choking device is placed at 1700 m along-hole (AH) depth.

In depleted reservoirs, the use of downhole chokes in a well can be challenging because the pressure drop across the choke device may be large, which may increase the risk for hydrate formation in the well. Moreover, the differential pressure across the device is very sensitive to small changes in the diameter of the choke. Therefore, the operational envelope of a well containing (a) downhole choke(s) can change as a result of erosion or abrasion of the device. Another disadvantage of employing downhole chokes is that it brings forth a higher chance of well activities to change the downhole chokes during the project's lifetime[32]. The downhole choke is especially useful in situations with a (very) low pressure reservoir. Therefore, at a late life stage of a CO_2 injection project, it is likely downhole chokes will not be necessary anymore, since the reservoir pressure may have increased sufficiently as a result of CO_2 injection[32].

An example of a project designed with downhole chokes is the L4-field in The Netherlands (operated by TotalEnergies), which will be fed from the Aramis infrastructure in the North Sea. L4 is a depleted field with very low reservoir pressure of around 20 bar. The injection philosophy is that two-phase flow is considered acceptable in this project and moreover that the injection site should be able to accommodate a continuous and uninterrupted injection window ("no uninjectable rates") during the entire life cycle of the project – preferably without having unique injection configuration for a given flow rate. The injection wells will have different tubing diameters, including one well with tapered tubing, in order to be able to accommodate all supply rates with different but non-unique well combinations.

Challenges for injection in the L4 reservoir is its high injectivity and the associated risk of extreme localized cooling. Installing three downhole chokes per well is proposed as a solution to increase pressure in the well. The L4 project will use multiple wells with different completion sizes, one of which includes tapered tubing[33]. The L4 project plans to demonstrate that the well completion design can be engineered to such an extent that it can increase a project's flexibility to deal with CO_2 supply variation whilst managing downhole conditions to within acceptable bounds.

3.3 Simulations of the dynamic response of a CO_2 T&S network

In this section, simulations are conducted to analyse an example network and illustrate the dynamic response of a T&S system (Figure 17). One reference scenario and four alternative scenarios are modelled. These four alternative scenarios are meant to simulate well failure as well as CO_2 supply variations (an increase as well as a decrease in supply) and the subsequent effects this has on the remaining storage sites in the system.

Table 3. Settings for dynamic simulations for a reference scenario.

Parameter	Value
Reservoir pressure at well array-1 Reservoir pressure at well array-2	150 bar 100 bar
Pressure set point	120 bar
Mass flow control to well array-2	30 kg/s
Ambient temperature sea water Ambient temperature air	5 °C 15 °C

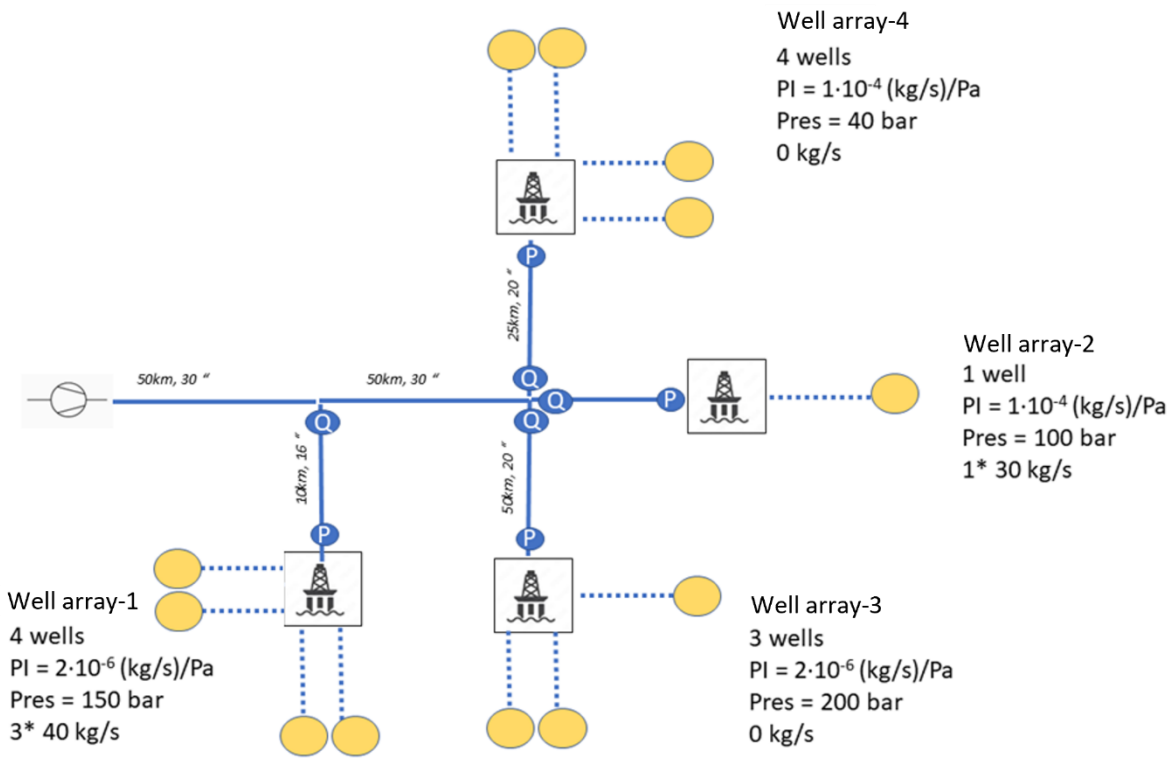

Figure 17. Reference network for the transport and storage of CO_2. The desired flow rate distribution is indicated. P and Q show location of pressure and flow control, respectively. The dynamic response results in this report do not include the flow to well arrays 3 and 4.

In the reference example, the change in flow rate at the inlet is done only for one hour as that mimics a temporary upset rather than a regular, planned change in flow rate. The total flow rate was set to 150 kg/s (3 wells each receiving 40 kg/s at well array-1 and 1 well receiving 30 kg/s at well array-2). For this operating point the wells at well array-1 are in the friction regime, which is a flow condition where frictional forces along the wellbore significantly influence the pressure and flow behaviour of the injected CO_2, in this case meaning the wells cannot handle any additional flow except by an increase of the manifold pressure. The model parameters in the reference scenario are given in Table 3. Table 4 and Table 5 provide an overview of the dynamic response scenarios.

Table 4. Overview of scenarios 1 and 2 for the dynamic response simulation.

Flow rate [kg/s]	Ref. scenario	Scenario 1	Scenario 2
Well array-1, well-1	40	CLOSED	50
Well array-1, well-2	40	60	50
Well array -1, well-3	40	60	50
Well array -2, well-2	30	30	CLOSED

Table 5. Overview of scenarios 3 and 4 for the dynamic response simulation.

Flow rate [kg/s]	Ref. scenario	Scenario 3	Scenario 4
Inlet	150	120	180

The pressure at the compressor discharge (i.e. the pipeline inlet) and the pressure at manifolds of well array-1 and well array-2 obtained from the simulations are presented and discussed in the following. The mass flow rate and temperature are taken at the wellhead of each well. In *scenario-1*, one well at well array-1 closes (Figure 18). In this example network there is no spare capacity without increasing the manifold pressure. As the flow to well array-2 is mass flow controlled, as soon as one well closes, the two remaining wells at well array-1 take extra flow, leading to a total flow to those wells of 60 kg/s (3 x 40 = 120 kg/s, divided over two wells). As all wells are in the friction-dominated regime with open wellhead chokes, the trunkline pressure increases rapidly. In this scenario it would take around 2 days before equilibrium is reached (even for the short network simulated here). The pressure in the trunk line increases to 210 bar relatively gradually such that this event can be detected by operators. To avoid a pressure increase, spare capacity must be available in other wells coupled to the network. In practice, the maximum allowable operating pressure of the pipeline is a factor in determining whether such pressure increases can be accommodated safely.

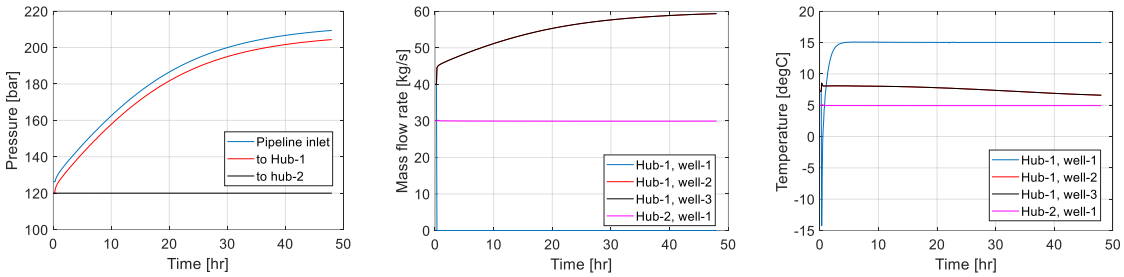

Figure 18. Results for scenario 1. One well at well array -1 closes. From left to right, pressure, mass flow rate and temperature, respectively. Well arrays are denoted as "Hubs".

In *scenario 2*, the well at well array-2 is closed (Figure 19). The response to the system is relatively similar to in scenario 1, except that the total flow is now fully divided over the wells in well array-1 (taking 50 kg/s each). The pipeline pressure now only increases to 155 bar.

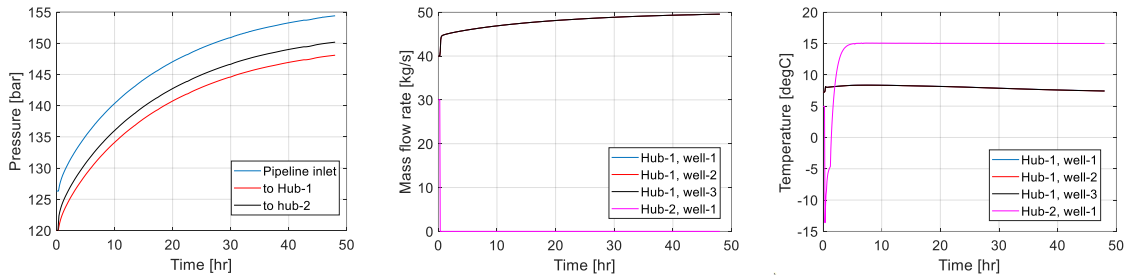

Figure 19. Results for scenario 2. The well at well array -2 closes. From left to right, pressure, mass flow rate, and temperature, respectively. Well arrays are denoted as "Hubs".

In *scenario 3*, the flow at the inlet drops by 20% for 1 hour (Figure 20). The total flow rate drops from 150 to 120 kg/s. As the flow to well array-2 is flow-controlled, the flow to that well array remains 30 kg/s. The wells at well array-1 would now receive 90 kg/s in steady state condition. In this scenario all three wells are fully open and the only control is the pressure control. Due to the dynamics in the system, the mass flow rate in the wells at well array-1 dips below 30 kg/s (28.3 kg/s per well) resulting in a dip in the temperature. The pressure dips from 126.3 bar to 123.5 bar. The return to steady state pressure takes 2.4 hour in pressure but a return to steady-state mass flow rate takes nearly 20 hours.

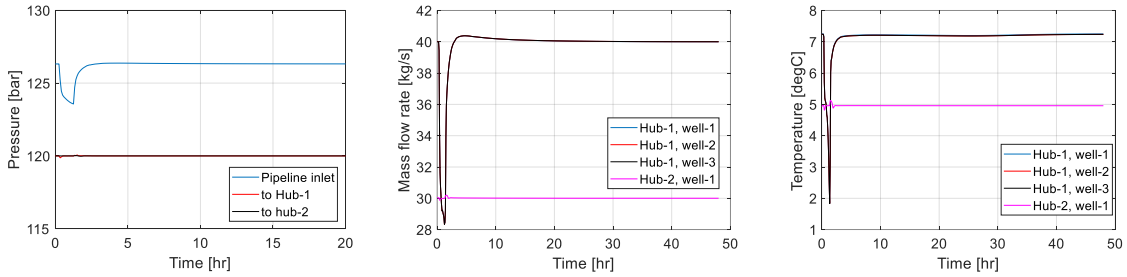

Figure 20. Results for scenario 3. The flow at the inlet drops for 1 hour with 20%. From left to right: pressure, mass flow rate, and temperature, respectively. Well arrays are denoted as "Hubs".

In the last scenario, *scenario 4* (Figure 21), the rate increases for one hour by 20% to 180 kg/s. The flow to well array-2 is still mass flow-controlled and therefore takes 30 kg/s, with the remaining 150 kg/s flowing to well array-1. No steady state is reached within the hour of increased injection, but the pressure increases from 126.3 to 132.8 bar. The flow rate at well array-1 only increases to 45 kg/s rather than the steady state solution of 50 kg/s. This higher flow rate has increased the manifold temperature at well array-1. Especially the fast increase in pressure demonstrates the limited buffer capacity present in the system.

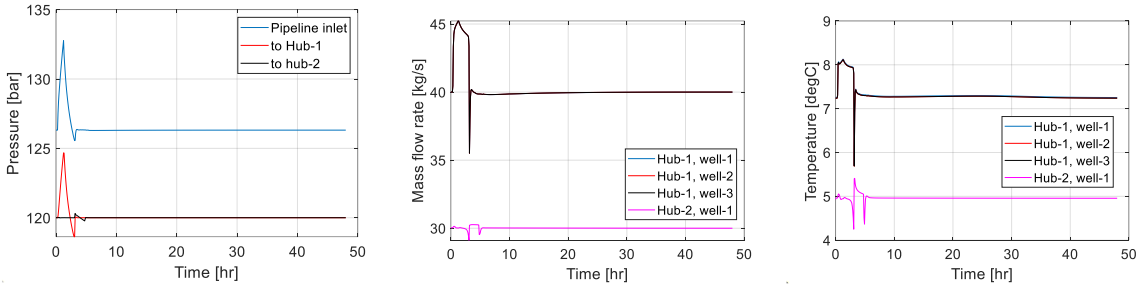

Figure 21. Results for scenario 4. The flow at the inlet increases for 1 hour with 20%. From left to right: pressure, mass flow rate, and temperature, respectively. Well arrays are denoted as "Hubs".

In a scenario where all wells are operating in the friction regime, the response to increased flow rates is a rapid increase in pipeline pressure. High mean operating pressures are required to solve this. If the wells are not in the friction regime, decreases in the flow rates can cause wells to transition to the gravity dominated regime (where gravitational forces significantly influence the behaviour and movement of injected CO_2), resulting in low wellhead temperatures (which may freeze the annulus fluids or results in temperatures outside of material specifications). This means that operating conditions need to be balanced with expected or allowed flow and pressure fluctuations across the wells connected to a T&S network.

In case the conditions are such that the wells at well array-1 are not fully in the friction regime, additional flow can be allocated to these wells without increasing the pressure. In that case, the response of the pipeline pressure is smaller (Figure 22). The downside, however, is that in case the flow drops, the consequence on the wellhead temperature is much larger (Figure 22).

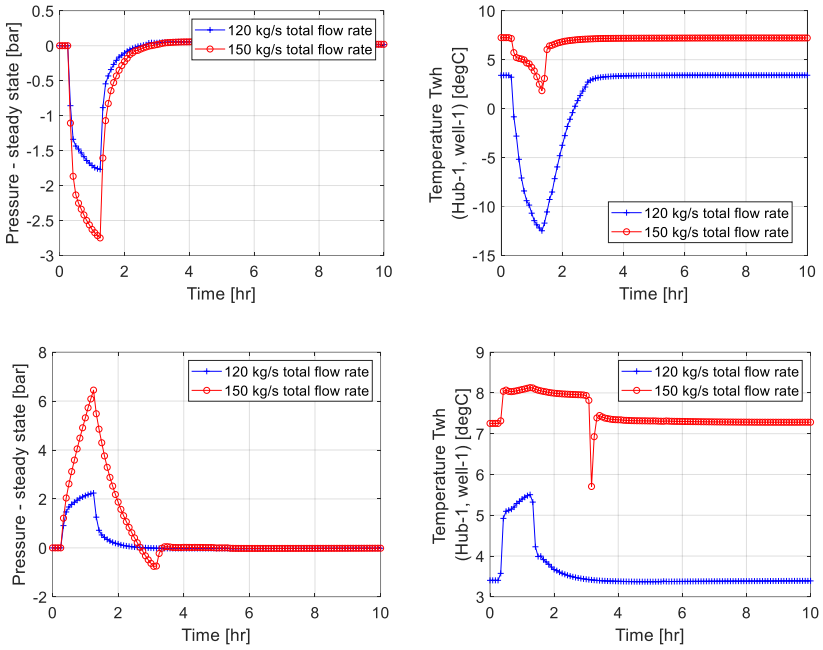

Figure 22. Comparison of dynamic response (left: pressure, right: temperature) for scenario 3 (top) and scenario 4 (bottom) with a total flow rate of 120 kg/s (blue) or 150 kg/s (red). The pipeline inlet pressure is plotted compared to the steady state pressure.

This small simulated network shows the potential dynamics of an operating CO_2 network. The dynamic behaviour as shown in this section demonstrates one of the large differences between a high pressure CO_2 network in comparison to a natural gas network. In a dynamic sense a CO_2 network will behave more similar to a network transporting a liquid than to a gas transportation network. Due to the fact that the CO_2 network operates at liquid/supercritical conditions, the packing capacity in the pipelines is limited. This means that upsets at the inlet (increase or decrease in supply rate to the network) almost directly lead to large pressure increases or decreases in the transport pipelines. Intermediate storage of CO_2 at the compressor station can reduce these pressure changes, however, there is a trade-off between associated costs and added flexibility, which in turn depends on installed tank capacity and minimum flow rate of the T&S system[25].

Wells with lower injectivity determine the required trunkline pressures if the wells are mass flow rate-controlled. A perhaps counter-intuitive fact related to using depleted fields for CO_2 injection is that lower-quality wells (i.e., wells that have not been the best producers of natural gas) can have a significant impact on T&S network operations for these wells may require a large operating pressure. In a complex network where the flows to the different well arrays are mass flow-controlled, one well array needs to absorb all 'remaining' flow due to the dynamics in the system and to counteract discrepancies and errors in flow meters. However, this also means that upsets in the system are mainly felt at that specific well array. In a network with multiple storage operators, such technical issues must be taken into account in the network Heads of Terms (see also Section 4).

This section has explained the interplay between reservoir conditions in depleted fields, the operational window that arises from these conditions and the subsequent engineering options available to a project developer. The dynamic simulation demonstrates the effect irregularities in CO_2 supply or one of the injection wells can have on a network shared by multiple storage sites or well arrays. Many future CCS projects are likely to follow a hubs and cluster approach with numerous emitters utilising a single collection network with one or more storage locations, potentially with varying operational bandwidth

present. It is advised that optimisation of the operating conditions is done on a network level rather than from the perspective of an individual storage site or well (array). Again, the “worst” well, or the well with the lowest injectivity, can require a large operating pressure which may be detrimental to the performance of other wells in the network. In order to optimise the performance of the entire network, the operating pressure in the transport pipeline could be the minimum required pressure to inject the supplied rates, rather than having pipeline pressure as dictated by a single well (array) or storage site. This approach, on a network level, could reduce costs as well as provide improved resilience to temporary variations in flow rate since redistribution of excess flow between the wells will be possible. In that sense, network optimisation could have a positive effect on the availability of a T&S network as a whole. Having complex networks with multiple users has obvious commercial and contractual implications where it comes to, for instance, CO_2 ownership, maintenance and outages and network optimisation/flow distribution – which are discussed in section 4.

4 Storage Regulations and Permitting Processes

Cross border movements of CO_2 for CCS purposes rely on effective legal and regulatory regimes no less than physical infrastructure, engineering capacity, and finance. Indeed, each of these is both enabled and constrained by regulatory regimes which authoritatively determine the ways in which CO_2 is moved and durably stored, how it is accounted for, how responsibility for reversals is dealt with, as well as the minutiae of how projects are made commercially viable. This section outlines these considerations at the levels of international law, regional law, and selected national jurisdictions. A number of substantive areas are focussed on, namely: framing considerations in international and national law (4.1); cross-border specific regulation (4.2); contractual arrangements (4.3); and emerging business models (4.4). As a consequence of varying degrees of transparency across jurisdictions, and for reasons of commercial confidentiality, these discussions are both necessarily incomplete but the most accurate statement of the matter as of 1 December 2024.

4.1 General Legal Considerations: International and Regional

4.1.1 The London Convention / London Protocol

During the development of the IPCC's methodology for "CO_2 Transport, Injection, and Geological Storage" in the early 2000s, carbon capture and storage (CCS) became a topic under the London Convention, an international treaty regulating marine dumping[1]. The 1996 Protocol expanded the scope to include the seabed as part of the marine environment, making subsurface storage of CO_2 potentially classifiable as marine dumping. Under the Convention, only substances listed in Annex I are exempt from this prohibition, provided they meet conditions outlined in Annex II, such as conducting Environmental Impact Assessments[2].

CCS was first considered by the London Convention's Scientific Group in 2003, and by 2006, the Annex I list was amended to include CO_2 as a permissible substance for marine disposal (LC 28/15 (6 Dec 2006), Annex 6). This amendment, adopted at the 28th Consultative Meeting in November 2006, entered into force in February 2007[3]. The amendment allowed the "disposal of CO_2 streams from CO_2 capture processes for sequestration," provided it complied with the Risk Assessment Framework developed by the Scientific Group. A critical requirement was that the CO_2 stream "consist overwhelmingly of carbon dioxide" and not include "wastes or other matters" (LC/SG 30/14 (Jul 2007), Annex 3). This allowed flexibility in CO_2 purity standards, supporting technological advancements[3]. The CO_2 Specific Guidelines also mandated comprehensive risk assessments, considering factors such as site integrity, human health, and impacts on the marine environment (LC/SG 30/14 (Jul 2007), Annex 3).

Regarding treaty procedures, the amendment to the London Convention's Annex permitting sub-seabed CO_2 storage was achieved through a straightforward majority vote. However, amending an article of the Convention requires not just approval by vote or consensus but also ratification. This distinction is critical in the context of cross-border CCS. Article 6 of the Protocol prohibits the "export of wastes or other matters to other countries for dumping or incineration at sea." This complicates CO_2 transportation for countries lacking suitable geological formations for CCS, such as Finland or Sweden. Conversely, for countries like the United Kingdom, which possess abundant geological capacity in depleted oil and gas (and saline aquifers) fields, this presents a significant opportunity, but only if CO_2 importation is allowed.

Recognizing the prohibition as a barrier to CCS development, the London Convention parties (see Figure 23) voted in 2009 to amend Article 6, allowing the "export of CO_2 for disposal in accordance with Annex 1" (2009 LP4, 30 October). However, this amendment requires ratification by two-thirds of states/parties to take effect, a threshold yet to be met as of December 2024, prompting concerns voiced by Secretary-

General Sekimizu of the IMO regarding the lack of ratifications. Hence in 2019 Norway and the Netherlands proposed a Resolution on Provisional Application of the 2009 Export Amendment. This was adopted and now enables countries to agree to export and import CO_2 for offshore geological storage, and still following the requirements of the 2009 Export Amendment.

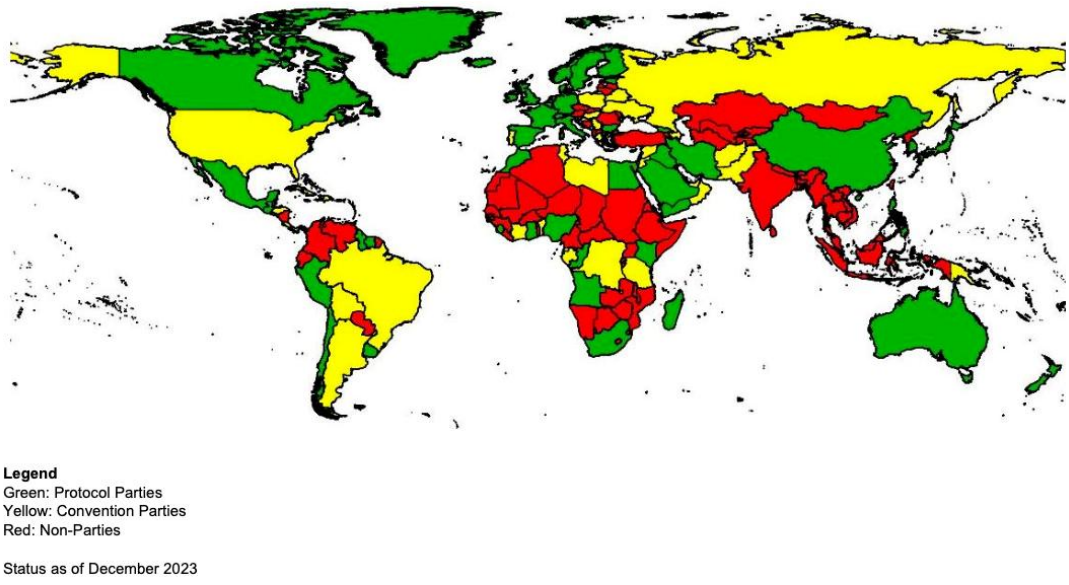

Figure 23. Map of parties (December 2023) to the London Convention/Protocol.

4.1.2 The Helsinki Convention

The Helsinki Convention (see Figure 24 for a map of contracting parties) similarly prohibits dumping CO_2 in the Baltic Sea[4]. This is particularly significant as the Baltic states have limited onshore storage options. Interpretations of the Helsinki Convention vary, with some interpreting that it does not prohibit CO_2 storage deep beneath the seabed, while others adopt a stricter reading, arguing that any such storage is prohibited. Changing the Helsinki Convention would require unanimous agreement among all member states, including Russia, whose stance on such a request remains unpredictable.

4.1.3 The OSPAR Convention

While the London Convention operates globally, regional instruments such as the OSPAR Convention[6] also play a role. The OSPAR Convention[20], aims to prevent and eliminate pollution in the North-East Atlantic[21].

The OSPAR Convention faced similar CCS challenges and followed the London Convention's lead in amending its Annexes II and III to allow CO_2 storage. These amendments, adopted in June 2007[7], came into force in October 2011 after sufficient ratifications. The 2007 process also included a Decision mandating guidelines for risk assessment, management processes, and prohibiting CO_2 in the ocean column.

The Helsinki Convention has 10 Contracting Parties which are also the members of HELCOM.

The Contracting Parties are represented by a Head of Delegation. In addition to the annual Commission meetings, the Heads of Delegation meet at least twice a year.

HELCOM uses the ISO 3166-1 alpha-2 (two-letter) country code abbreviations:

DE – Germany
DK – Denmark
EE – Estonia
EU – European Union
FI – Finland
LT – Lithuania
LV – Latvia
PL – Poland
RU – Russia
SE – Sweden

Figure 24. Map of contracting parties to the Helsinki Convention[35].

One reason for the successful ratifications of the OSPAR Convention amendments was that it is a European agreement.

4.1.4 European Union: Regulatory Framework

In 2007 the EU Council, as part of its "Action Plan for Energy Policy in Europe", placed particular emphasis on CCS promising strengthened R&D and aiming for 12 demonstration projects by 2015[8]. While these projects have not materialised, a regulatory framework has.

The EU's regulatory framework for CCS has two main purposes – environmental protection, and financial support – and the speed with which it moved from draft to concluded legislation is testament to a high degree of interest alignment across Member States, European Institutions and interest groups[9]. The CCS Directive[10] recalls many of the features discussed above – the objective of permanent storage, prohibition of ocean storage, requirement of permitting for exploration and storage, an emphasis on site selection, risk assessment and monitoring – but also links with the EU's trading scheme in important ways. As regards environmental protection, monitoring is linked to that required by the ETS such that "liability for climate damage as a result of leakages is covered by the inclusion of storage sites in Directive 2003/87/EC, which requires surrender of emissions trading allowances for any leaked emissions"[11]– a rigorous level of monitoring. Furthermore, operators are required to provide financial security (i.e. to

provide for thirty years of monitoring[12]).However, after closure of the storage site, liability transfers from the operator to the State (or "competent authority" in the language of the Directive) after no less than twenty years[13]. This transfer of responsibility takes place after a process of 'history matching' whereby the monitored CO_2 is demonstrated to have behaved in a manner consistent with the operator's ex ante modelling and there is no detectable leakage, and the CO_2 is moving towards long-term stabilisation. Finally, the CCS Directive removes barriers to the operation of the technology as contained in other instruments of EU law[14].

Moreover, the CCS Directive forms the legal framework for the safe geological storage of CO_2 within the EU[36]. The Directive primarily governs projects aimed at the permanent containment of CO_2, while the capture and transport aspects are mainly covered by other EU environmental legislation, such as the Environmental Impact Assessment Directive[37] and the Industrial Emissions Directive, with amendments introduced by the CCS Directive[30]. Additionally, the Emissions Trading System Directive (ETS) establishes the EU Emissions Trading System, which governs CO_2 emissions and trading[38].

4.2 Legal Considerations: National level

4.2.1. US Federal Requirements

The EU's approach may be briefly contrasted with that in North America. In the USA Federal requirements under the Underground Injection Control Program for Carbon Dioxide Geological Sequestration have established a new class of wells ('Class VI') for CCS[15]. Although primarily concerned with safeguarding drinking water, these rules also feature permitting, site characterization, financial responsibility, post injection site care (with a default of 50 years). U.S. CO_2 pipeline projects are often subject to a mix of federal, state, and local regulations, which may not always align. For example, a pipeline may receive state or federal approval, but still face opposition or additional requirements from local governments. This creates a complex regulatory environment that increases cost and financial risk[16].

Enhanced Oil Recovery (EOR) has played a crucial role in financing CCS in North America. EOR involves using CO_2 to extract additional oil from wells after primary extraction. This method is well-established in the USA, where companies traditionally pay for CO_2. When combined with CCS, EOR helps fund storage, as firms are willing to purchase the CO_2, which would otherwise be a cost. Approximately 50% of injected CO_2 remains underground during EOR, an inconvenience for oil companies but beneficial for carbon storage and climate objectives. EOR has also provided real-world data on CO_2 behaviour underground, serving as a practical testbed for CCS. However, in the European Union, provisions in the original CCS Directive limited the integration of EOR with CCS storage. This gap may be addressed in future reviews and reforms of the Directive[17].

There is also growing interest in the emerging concept of the Carbon Take Back Obligation (CTBO), which could require fossil fuel producers to store an equivalent amount of CO_2 as they emit. Storage through EOR could potentially serve as an early implementation of CTBO, though discussions around the concept are still ongoing.

4.2.2. Denmark

In January 2022, Denmark ratified the necessary articles of the London Protocol. Later, in August 2022[18], Denmark opened its first tender for CO_2 investigation and storage licenses for offshore storage. The first full-scale investigation licenses were issued in February 2023, with injection projected to start in 2025. Denmark has integrated the CCS Directive into several legislative frameworks, including the Danish Storage Regulation[19] and the Danish Maritime Protection Act[20]. The Environmental Protection Act[21] also

regulates when environmental permits are required, such as for CO_2 capture projects[22]. Various agencies, including the Energy Agency and the Environmental Protection Agency, collaborate to review CCS permits[23].

For CO_2 transportation, Denmark has established some regulations, though new legislation is needed, especially concerning pipelines over 800 mm in diameter and longer than 40 km, which require environmental impact assessments[24]. The Danish Marine Environment Act generally prohibits dumping materials in the sea and seabed, but a 2021 amendment allows for the exemption of CO_2 storage below the subsurface[25]. Guidelines for CO_2 geological storage are detailed in the Act on Use of the Danish Subsoil (the Subsoil Act)[26] and the CCS order[27].

In September 2022, Denmark and Flanders, Belgium, signed a bilateral agreement facilitating CO_2 transport between the two countries for geological storage. While this agreement aligns with broader international cooperation on CCS, it operates independently from the London Protocol, focusing on practical arrangements for cross-border transport of CO_2 for storage[28].

4.2.3. Iceland and Norway

Other Nordic countries, including Iceland, and Norway, are parties to the London Protocol. In 2023, Norway, with Denmark, and Sweden accepted the provisional application of the amendment to Article 6 of the Protocol[29]. These countries are also working on bilateral agreements for CO_2 export and geological storage[30]. Other agreements relevant to CCS activities, ratified by Nordic countries and others (including the EU), include the OSPAR Convention[31], which aims to prevent and eliminate pollution in the North-East Atlantic[32].

The Convention on Biological Diversity (CBD) has also been ratified by all Nordic countries[33], focusing on biodiversity conservation and the sustainable use of resources[34]. Another key agreement is the Helsinki Convention, which covers the protection of the Baltic Sea and has been ratified by all Nordic states, including Sweden, Finland, and Denmark, as well as the EU[35].

4.2.3.1. Iceland

Similarly to Denmark, the CCS Directive has been transposed into Icelandic law, which initially prohibited CO_2 storage on an industrial scale[23]. Key provisions for industrial-scale CO_2 storage are found in the Sanitation and Pollution Prevention Act[39]. In 2019, the Icelandic government, along with Carbfix and five other companies, signed a declaration of intent to explore the use of the Carbfix method to reduce emissions from heavy industries[40]. Iceland is currently refining its legal frameworks, including those related to CO_2 import and the EU ETS[41].

Operating permits for geological CO_2 storage are regulated under the Health and Pollution Prevention Act.[42] The 2022 amendment to the Act on Health and Pollution Control now permits CO_2 storage within Iceland's territory, its exclusive economic zone, and the continental shelf[41]. Iceland's legislation distinguishes between mineral CO_2 storage, such as the Carbfix method, and conventional geological storage. Notably, the CCS Directive's 30-year monitoring requirement for potential leaks does not apply to mineral CO_2 storage[41].

4.2.3.2. Norway

Similarly to the aforementioned countries, Norway has implemented the CCS Directive through one new regulation and amendments to two existing regulations. The new Storage Regulation[43] was introduced, alongside additional chapters in the Petroleum Regulation[44] and the Pollution Regulation[45]. The new Storage Regulation is inspired by petroleum regulations, with CCS requirements incorporated into both

the Petroleum and Pollution Regulations. The permitting system is divided: the Petroleum Regulation covers CCS related to petroleum activities, while the Storage Regulation covers all other CCS activities.

Norway's CCS framework is permit-based, with permits required for all exploration and exploitation activities, as these resources are considered state property[30]. The Pollution Regulation specifically addresses permits for activities that may cause pollution, including CO_2 capture for geological storage from certain facilities.

Norway's implementation of the CCS Directive allows for offshore geological storage beneath the seabed within the continental shelf. Any party intending to inject and store CO_2 in geological formations must obtain a permit from the Norwegian Environmental Agency. The Storage Regulation also stipulates that only the State can explore or exploit underwater reservoirs on the continental shelf[46] for CO_2 storage or transport CO_2 without the necessary permits.

In 2021, Norway and the Netherlands signed a Memorandum of Understanding to finalize a bilateral agreement on CCS activities[47].

4.2.4. Australia

Australia has developed a regulatory framework for CCS projects at both Commonwealth and state levels, with regulations varying across States and Territories, some having project-specific laws[48]. At the Federal level, CCS is governed by the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGSA), which covers offshore areas up to 270 km from the coastline[49]. This act provides for GHG assessment permits and injection licenses[50]. The National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) regulates offshore CCS, and additional environmental approvals may be required under the Environmental Protection and Biodiversity Conservation Act 1999 (EPBC Act), depending on the project's impact[51].

Other relevant federal legislation includes the Environment Protection (Sea Dumping) Act 1981[52] and the National Greenhouse and Energy Reporting Act 2007[53]. At the state level, CCS regulation varies: Victoria has the Greenhouse Gas Geological Sequestration Act 2008[54] and Queensland the Greenhouse Gas Storage Act 2009[55]. Western Australia's Barrow Island [56]CCS project is governed by the Barrow Island Act 2003. Western Australia is also considering amendments to introduce a GHG legislative regime similar to the Commonwealth's OPGGSA.

However, States such as New South Wales, Tasmania, and the Northern Territory currently lack specific CCS legislation[57]. This absence does not prevent the development of CCS projects but indicates that required approvals are not yet covered by specific laws. Despite these gaps, ongoing regulatory and policy evolution is expected to shape the future of CCS in Australia[58].

4.2.5. Middle East (MENA region)

In the MENA region, CCS projects are being developed in countries such as Saudi Arabia, the UAE, and Qatar, which are members of the Gulf Cooperation Council (GCC). As non-Annex I countries under the UNFCCC, they must submit agreements outlining their CCS projects and develop regulations related to site selection, CO_2 ownership, infrastructure access, liability for permanent storage, and addressing any net reversals of storage[59].

The GCC comprises six member states, including Saudi Arabia, the UAE, and Qatar. Although none of these countries have CCS-specific regulations, existing frameworks like Saudi Arabia's General Environmental Law, Qatar's Law No. 30 (2002), and UAE's Federal Law No. 24 (1999)[60] govern Environmental Impact Assessments (EIAs) for projects. A significant regulatory issue is aligning CCS-EOR

activities with existing petroleum laws and addressing the challenges of post-closure CO_2 migration, especially with potential transboundary impacts due to the region's shared oil and gas resources.

The region lacks specific CCS laws[61], but regional conventions such as the GCC Customs Union [62]and the Kuwait Convention[63] (focused on the marine environment) indirectly influence the regulatory landscape. Most CCS projects in the GCC are state-driven, developed by state-owned companies with governmental funding, although the financial strategies have often been ad-hoc. Key future challenges involve integrating CCS with petroleum-based economies and clarifying legal aspects of CO_2 ownership and liability.

Moreover, there is increasing interest in scaling up CCS in the region to meet growing climate commitments and leverage enhanced oil recovery (EOR), where CO_2 is injected into oil reservoirs to boost production while permanently storing CO_2 (adding the objective of permanent CO_2 storage to that of enhancing oil production). The intersection of CCS and EOR poses both opportunities and regulatory challenges, as the projects are primarily developed within the existing framework of petroleum activities. The absence of clear, dedicated CCS regulations will need to be addressed as the region seeks to expand its role in global CCS efforts, especially in relation to managing long-term storage risks and ensuring the legal certainty of cross-border projects[64].

4.2.6. China

China currently lacks a comprehensive federal regulatory framework for CO_2 storage. Instead, the country relies on specific organizations such as the China Classification Society for expertise and safety assurance in the absence of formal permitting processes. This has left the development of CCS projects primarily in the hands of large state-owned enterprises, like the China National Offshore Oil Corporation (CNOOC).

Despite the progress in offshore CCS technology, there are no formal federal approvals or licensing processes for these operations. Much of the technical expertise resides with state-owned companies like CNOOC, which also manage their own performance audits and safety standards. Shipping transport of CO_2 is not yet developed in China, with onshore CO_2 transport primarily conducted by road tankers due to the small scale of existing projects.

On the policy side, support for CCS remains sparse compared to Europe, with general federal guidance but limited detailed co-development funding or supervision. A notable exception is Guangdong province, where several CCS clusters are being planned along the Pearl River, targeting key sectors like refineries, coal, and gas power plants. These clusters are aligned with China’s Belt and Road initiative, which may help accelerate the development of CCS-related regulation and infrastructure.

China has also established an Emissions Trading Scheme (ETS) as a pilot in seven regions, covering over 1,000 Mt CO_2 emissions. While the scheme has reduced emissions in some cities, issues like carbon leakage to nearby regions have limited its overall impact. In 2022, China introduced the Interim Regulations on the Management of Carbon Emission Trading, which is the only relevant carbon pricing policy currently in place. Further development of the national carbon market, higher carbon prices, and mandatory CO_2 capture policies for sectors like coal and petrochemicals will be necessary for China to meet its 2030 emissions targets.

In the coming years, China will need to develop national CO_2 pipelines, improve geological storage standards, and scale up large integrated CCS projects in key industries such as power, steel, cement, and petrochemicals to meet its climate goals.

4.3 Cross-Border CO_2 Transport

Cross-border CO_2 transport has become a focal point for CCS projects, especially for countries seeking to collaborate on large-scale CCS infrastructure. Several legal frameworks and treaties govern these operations, ensuring that international regulations are adhered to while promoting the safe and efficient transport of CO_2.

4.3.1. International Regulatory Frameworks

4.3.1.1. London Protocol

The London Protocol, which is focussed on the control of maritime pollution, is central to cross-border CO_2 transport regulation and storage. Under the 2019 resolution, the export of CO_2 for disposal in accordance with Annex 1 is allowed if there is an agreement between the involved countries. These agreements, which can be in the form of Memoranda of Understanding (MoU) or treaties, must confirm the allocation of permitting responsibilities and ensure compliance with the Protocol and other international laws, including UNCLOS (United Nations Convention on the Law of the Sea).

This requirement applies to the exporting and receiving countries but excludes transit nations[65]. In cases where CO_2 is being exported to a non-contracting country, the exporting state is responsible for ensuring compliance with the London Protocol's provisions, including those in Annex 2. In 2023, Norway, Denmark, and Sweden accepted the provisional application of the amendment to Article 6 of the Protocol[29]. These countries are also working on bilateral agreements for CO_2 export and geological storage[30].

Despite the amendment enabling CO_2 export, the impact of the London Protocol has been limited by slow ratifications and political barriers[66]. The approach currently taken is to use bilateral agreements between states to agree to export and import CO_2 for offshore geological storage, using the Resolution proposed by Norway and the Netherlands (see 4.1.1), still following the requirements of the 2009 Export Amendment.

4.3.1.2. Other Frameworks

In addition to the London Protocol, several other international agreements regulate the transport of CO_2 across borders. SOLAS (International Convention for the Safety of Life at Sea) and MARPOL (International Convention for the Prevention of Pollution from Ships) regulate CO_2 transport by sea without impeding its movement. Although there is some ambiguity as to whether the Basel Convention and the Bamako Convention on hazardous waste apply in this context, the prevailing view is that they do not.

However, the fragmented regulatory framework calls for a more unified approach to ensure the accurate accounting of emissions reductions. This requires robust Monitoring, Reporting, and Verification (MRV) systems to ensure that CCS projects are credited appropriately under frameworks like the UNFCCC (United Nations Framework Convention on Climate Change). The ISO 27913:2016 standard provides guidelines for designing and operating CO_2 pipeline systems safely and efficiently. Updates to this standard are expected to incorporate the latest knowledge from the industry[68].

4.3.2. EU and EEA Regulatory Frameworks

4.3.2.1. Carbon Capture and Storage Directive (Directive 2009/31/EC)

The CCS Directive (Directive 2009/31/EC) sets regulatory standards for CO_2 storage within the European Union but does not specifically address cross-border transport[69]. The Directive is compatible with the provisions of the London Protocol and international laws such as UNCLOS. In September 2022, the

European Commission stated that existing EU laws, including the CCS Directive and the EU Emission Trading System (ETS) Directive (Directive 2003/87/EC), provide a sufficient legal framework for cross-border CO_2 transport under the London Protocol[70].

The CCS Directive also aims to ensure fair and open access to CO_2 transport networks. Operators must consider capacity and technical compatibility when granting access to their infrastructure. However, the Directive defines CO_2 transport networks as solely comprising pipelines, excluding other modes like ships, barges, trucks, and trains. This narrow definition could hinder the scalability and economic feasibility of CCS projects in regions where pipeline infrastructure is underdeveloped[71].

4.3.2.2. EU Emission Trading System Directive (Directive 2003/87/EC)

Annex I of the ETS Directive covers sectors including electricity, heat generation, and industrial production and was extended to maritime transport in January 2024[72]. This inclusion introduces additional compliance requirements for CCS projects transporting CO_2 via ship. Commercial ships calling at EU ports must acquire and surrender emissions allowances for their CO_2 emissions. The inclusion will be phased, with companies initially responsible for 40% of their emissions in 2024, 70% in 2025, and 100% from 2026 onwards. This imposes operational and financial burdens on shipping companies, which must account for CO_2 emissions and comply with monitoring, reporting and verification (MRV) systems.

The ETS allows for the deduction of CO_2 emissions transported and stored within the EU from a company's ETS liabilities, but not for CO_2 shipped to non-EU countries, like the UK. This restriction discourages cross-border transport outside of the EU. Aligning the EU ETS with other schemes, such as the UK ETS, could facilitate cross-border CO_2 transport through mutual recognition agreements, ensuring appropriate credits for CCS activities regardless of storage location [73].

In addition, transport via ship was not initially included in the ETS scheme, which focused on pipelines. In 2019, Norway sought clarification from the EU Commission, which endorsed the interpretation that CO_2 transported by ship could be treated like pipeline transport under the ETS. However, this was based on legal opinion, not binding legislation. The revised EU ETS Directive now includes all CO_2 transport modes, but the current MRR defines "transport network" as pipelines only, creating a misalignment. Article 49 of the MRR must be amended to allow CO_2 deductions for all transport modes, aligning it with the revised EU ETS Directive[74]. This would support the development of CCS projects by resolving inconsistencies in emissions deduction and liability transfer between capture, transport, and storage operators.

4.3.2.3. Recommendations

The observations made in the preceding sections lead to the following recommendations.

- Align ETS Systems: develop agreements between the EU and other ETS schemes, such as the UK ETS, to ensure mutual recognition of CO_2 storage. This would involve standardising metering and verification processes and ensuring that emissions reductions are correctly accounted for and deducted from the capturing entity's liabilities[75].
- Expand ETS Coverage: amend the Monitoring and Reporting Regulation (MRR) to explicitly include all modes of CO_2 transport to ensure a more holistic regulatory approach (NB. work is underway to include shipping).
- Streamline Permitting Processes: build regulatory support capacity by ensuring planning and permitting bodies are adequately resourced. Fast-track permitting for CCS projects should be allowed to reduce administrative delays[76]. Simplifying and accelerating the permitting process would make it easier for developers to navigate the regulatory landscape, encouraging more investment in

CCS infrastructure. This could involve creating dedicated teams within regulatory bodies to handle CCS permits and establishing clear timelines for decision-making.

4.3.3. United States

The US has a well-established regulatory framework for CCS, largely driven by its history of Enhanced Oil Recovery (EOR), which has traditionally used CO_2 to increase oil production. However, when it comes to cross-border CO_2 transport, the regulatory system is fragmented. Different federal, state, and international agreements govern these processes, resulting in a patchwork of regulations that can complicate cross-border projects[152].

4.3.4. Canada

In Canada, the regulation of CCS is managed both federally and provincially, with significant involvement from provinces like Alberta, where oil and gas infrastructure is heavily developed. Cross-border CO_2 transport follows federal guidelines, but each province can impose its own regulations, creating a multi-layered regulatory framework.

4.3.5. Liability Regimes

Liability for CO_2 transport varies significantly based on the mode of transport. For shipping, international conventions like the Convention on Limitation of Liability for Maritime Claims (LLMC) and the potential adoption of the Hazardous and Noxious Substances (HNS) Convention set the liability limits for shipowners. These frameworks help define who is responsible in the event of a spill or leakage during transportation.

In contrast, for pipeline transport, liability is primarily determined by national laws, which leads to a lack of uniformity across borders. This inconsistency in liability regimes can create challenges for companies involved in cross-border CO_2 transport, as they need to navigate different regulations based on the transport method used.

4.3.5.1. Recommendations

- Harmonise Liability Frameworks: develop standardised international guidelines for CO_2 transport liability that align with disparate national and international regulations. This could involve adopting elements from the LLMC and applying them to pipeline transport to ensure consistent liability limits and conditions. Harmonising liability frameworks would provide greater certainty for companies involved in CO_2 transport, reducing the risks associated with cross-border projects.
- Insurance Market Support: encourage state intervention and regulatory support to create a more favourable insurance market for CO_2 transport. This could involve providing subsidies or guarantees to insurers to reduce premiums and encourage more insurers to enter the market[77]. By making insurance more accessible and affordable, governments can help mitigate the financial risks associated with CO_2 transport, encouraging more companies to participate in cross-border projects.

4.3.6. Facilitating an Open-access Cross-border CO_2 Transport Network

The ownership models for CO_2 transport infrastructure can influence accessibility and cost efficiency. Private carrier models, where pipelines are owned and operated primarily for internal purposes, do not guarantee third-party access. In contrast, common carrier models offer transport services to third parties under standardised terms and conditions, promoting equitable access. To create an efficient and open-access cross-border CO_2 transport network, it is essential to address the regulatory and logistical

challenges associated with CO_2 transport. This involves developing standardised guidelines for CO_2 ownership and transfer, ensuring that CO_2 transport infrastructure is accessible to all potential users, and promoting collaboration between stakeholders.

4.3.6.1. Recommendations

- Adopt a Common Carrier Model: encourage the adoption of a common carrier model for CO_2 pipelines, ensuring that third-party users can access transport networks under non-discriminatory terms. This would be especially important for publicly funded infrastructure projects, where equitable access should be guaranteed to foster collaboration and maximize the use of the network.
- CO_2 Ownership Transfer Guidelines: develop clear guidelines for the ownership transfer of CO_2 across the value chain, especially for projects that are not vertically integrated. These guidelines should specify the points at which ownership (and thus liability) is transferred, as well as the standards for CO_2 purity and the tracking of transported quantities. Such clarity would reduce uncertainties and potential disputes between transport operators and storage facilities, ensuring smoother cross-border CO_2 transport operations.

4.4. Contractual Interactions

All interactions between CCS actors and stakeholders are governed by contract. Governmental involvement in CCS projects fluctuates between jurisdictions[78], however contract still forms the legal foundation through which these projects function between both public and private entities. A combination of commercial sensitivity and nascence dictates that the majority of these contracts in existence are not available publicly, which severely restricts the data available for the purposes of this section. However, certain large-scale CCS projects have made available their contractual packages, particularly in relation to transport and storage (T&S). These projects are located primarily in Europe; however jurisdictions further afield, such as Australia and Indonesia, are also looking to scale up CCS in the coming years. Outside Europe, there are several jurisdictions with comparatively advanced CCS, yet less available data (for example China[79]) or relatively incomparable unique systems (for example the USA[80]). Future research on contracts in these jurisdictions is required to contribute to a global understanding of CCS contractual relationships.

The contractual structure of CCS projects varies depending on the type of system, whether linear or hub/cluster, and the variety of parties involved (for example if there are separate or multiple T&S operators). The contractual information available revolves primarily around CCS hubs. There is a range of benefits to hub formation[81], however one of the more complex elements of hubs is the level of complexity within contractual systems. An example of this is Teesside in the UK, forming part of the East Coast Cluster. Prior to final investment decision (FID), nine T&S contractors have been engaged, across eight contract packages[82]. Each of these packages requires to be negotiated and in place prior to FID and operationalisation. A high volume of parties creates complexity, as there may be non-standardised nuances in each contract, even in jurisdictions (such as the UK) with government-provided business models[83] and a specific T&S 'CCS Network Code'[84].

4.4.1. Contractual rights and obligations with regard to upsets, CO_2 distribution and ownership dynamics within large T&S systems with multiple emitters and storage operators

The scenario of large T&S systems with multiple emitters and storage operators can perhaps be explored somewhat definitively on a technical basis, however obstacles exist when attempting to analyse contractual relationships in these flexible types of system. Contractual structures without a direct or

specific designated storage facility are not currently in operation, and overall, there is only a relatively small number of CCS projects in operation to date[85]. However, CCS contracts in circulation provide a strong demonstration of the obligations placed on parties to various types of CCS chain, and (in the case of hubs) outline the contractual relationships in place between multiple emitters and the T&S operator. One obvious gap therefore lies in the ability to analyse the contractual relationships between multiple storage operators. A review of existing contractual relationships provides a foundational review and a blueprint from which to construct the contractual relations of future projects which may include multiple storage operator scenarios.

4.4.2. Contractual rights and obligations of emitters

4.4.2.1. Port of Rotterdam CO_2 Transport Hub and Offshore Storage (Porthos)

The Porthos project is one of the most important and developed cross-border case studies in Europe, with FID in place and operationalisation scheduled for 2026[86]. The publicly available standard T&S terms and conditions demonstrate the contractual relationship between the T&S operator and each customer/emitter[87]. This is separate from the party-specific conditions which are agreed between the T&S operator and individual emitters and held privately within the 'transport capacity and storage space agreement'[88], which forms the front end of the overall contract. At a very broad level, the Porthos transport system comprises the connection of the onshore pipeline to the emitter's facility or transport system, including the compressor station, and the storage system comprises the offshore pipeline to the depleted gas reservoirs and wells[89].

Within the standard terms and conditions, the reduction or non-availability of the transport and/or storage systems is differentiated into planned maintenance and unplanned outages. The maintenance obligations which sit with the T&S operator are set out at *4.3.3.1* below. Although the relevant emitters are to be consulted regarding the planning and undertaking of maintenance, they bear no explicit contractual obligations with regard to T&S maintenance.

Outages encompass all non-availability of the T&S network which does not fall under the category of maintenance, or for reasons of force majeure[90]. The following outage scenarios necessitate that the relevant emitters continue to pay their agreed fees to the T&S operator, due to the outage not being the fault of the T&S operator:

- the aggregate transport capacity from all emitters (in a given hour) falls below technical minimum flow;
- the sum of CO_2 quantity received from emitters is below technical minimum flow;
- the sum of the metered quantities received exceeds the technical ramp rate; or
- the delivery of CO_2 from the emitter is out with the terms of the contract[91].

There is little contractual information available in relation to issues of CO_2 distribution and ownership dynamics during maintenance and outages. Under the Porthos terms and conditions, ordinarily an emitter is contractually obliged to deliver CO_2 to the T&S system that has been captured at the emitter's facility[92]. However, if an emitter's capture system or facility is not available due to an outage or maintenance, they may deliver CO_2 from a third party, in line with the emitter's transport capacity[92]. If an outage lasts for a prolonged period and exceeds a timeline cap outlined in the contract, emitters shall be entitled to terminate their contracts with the T&S operator. Emitters cannot terminate for this reason if the prolonged outage is their fault or the fault of any other emitter[93]. When an emitter terminates its contract with the T&S operator due to a prolonged outage, the emitter loses all rights to its agreed

transport capacity and storage space. This transport capacity and storage space then reverts to the T&S operator[94].

4.4.2.2. UK Hubs

The UK has several large CCS hubs in development[95], to which the UK Government's framework of business models and CCS Network Code will apply. The accompanying Heads of Terms to the Network Code, which forms one of the fundamental documents governing T&S contracts in the UK, is under review at the time of writing, following the recent closing of a governmental consultation[96]. The consequence of this is that these contract terms will likely change prior to future use by CCS hubs.

The existing contract terms contained in the Network Code bind T&S operators and emitters. Within the Network Code, the T&S network comprises the onshore transportation system, the offshore pipeline and the storage complex[97]. There are certain similarities between the UK's standard terms and the Porthos contract terms. Among these is the differentiation between maintenance and outages. There is a clear focus on cooperation between the parties, whereby all maintenance of either emitter facilities or the T&S system should be communicated and co-ordinated between the parties for minimum disruption to operationalisation[98].

During periods of unplanned outage in the T&S network, which the Network Code describes as a 'capacity constraint', emitters are still required to pay full capacity and network charges, unless:

- the constrained capacity is for any reason other than maintenance;
- the affected emitter cannot utilise any capacity due to the constraint, for a specified number of days; and
- the T&S operator's business interruption insurance covers the capacity constraint (see more below on insurance)[99].

In the above cases, the emitter's charges are reduced to reflect only the capacity utilised[100]. Similar to the termination provisions of the Porthos contract, if a capacity constraint is prolonged, the emitter may give notice to cease being a user of the T&S network entirely[101].

One final observation from a UK perspective is the role of liability caps and insurance in T&S contracts. The UK Government has proposed 'worst case scenario' liability caps on property damage and third-party liability for both emitters and T&S operators, for the purposes of accommodating small emitters who might otherwise be priced out of CCS projects if they could not obtain the requisite insurance to cover the applicable liability cap[102]. Having explicit liabilities outlined in the Network Code means parties to the contract understand their exposure and are treated equally, without the scope for negotiating bespoke levels of liability between different emitters and T&S operators[103].

4.4.3. Contractual rights and obligations of T&S operators

4.4.3.1. Porthos

The T&S operator is contractually responsible for the transport of CO_2 in its transport system[104]. For planned maintenance, emitters are notified of reductions or non-availability of the systems. Although the T&S operator is required to notify emitters of maintenance, the timing of maintenance remains at the discretion of the T&S operator[105]. Similar to maintenance, the T&S operator is required to provide notice to emitters for an outage[106].

As delineated at *4.3.2.1* above, the emitter must continue to pay fees during outages which are not the fault of the T&S operator. For all outages, the T&S operator must establish the root cause as soon as possible, and either solve or mitigate said cause, whilst keeping the emitter informed of these actions[107].

Sole responsibility and liability for these other outages lies with the T&S operator, however the emitter may offer advice or be consulted in relation to solving or mitigating the outage[108].

The Porthos contract terms and conditions provide a clear allocation of responsibility between parties. It is unclear from these contractual positions what the balance of responsibilities would be between multiple storage operators, but the landscape in which those responsibilities will be situated can be drawn from the current responsibilities and liabilities of emitters and T&S operators.

4.4.3.2. UK Hubs

The obligations of T&S operators are contained within the Network Code and associated Heads of Terms. Beyond the mutual obligation between parties to communicate any outages, the T&S operator bears obligations in relation to unplanned outages. In the case of a capacity constraint (unplanned outage) in the T&S network, the T&S operator must record the details of this under the contract and also for the purposes of its T&S licence[109]. The UK Government's crucial role in CCS dictates their involvement at a contractual level. The T&S operator not only carries responsibilities and obligations towards emitters, but also towards the government and governmental bodies for the purposes of complying with its T&S licence.

Beyond simply recording a capacity constraint, the T&S operator must publish available information about the constraint to affected emitters, including how the T&S operator intends to rectify the issue[110].

From the perspective of CO_2 distribution and ownership, the Network Code allows for CO_2 delivery to be declined. During events which constrain capacity, the T&S operator has the right to reject delivery of normal levels of CO_2 from emitters[111], changing the ownership dynamic between emitter and T&S operator. Within the UK system, during outages or network capacity constraints the T&S operator will apply a reduction of the registered capacity of constrained users of the network (emitters). If affected emitters are unable to utilise the reduced capacity, the T&S operator, as a last resort, will be required to deploy certain capacity optimisation principles, which may involve a redistribution of capacity and surplus capacity to certain emitters[112]. The T&S operator must try to maximise the number of constrained users it is providing availability to in these circumstances[113]. Under its licence, the T&S operator will be obligated to act in a non-discriminatory manner in terms of capacity redistribution[114]. This scenario demonstrates a balanced approach to capacity distribution. It is not confirmed if this approach will be taken in other jurisdictions pursuing CCS hubs.

The Code takes a broader stance than other available contract information across jurisdictions, in that it intends to dictate arrangements in future for T&S operators in scenarios where there are multiple T&S networks or multiple T&S operators within a network[115]. The scenario whereby the onshore and offshore elements of the T&S network are owned and controlled separately is outlined in the Network Code, but not catered for in detail, therefore there are no in-depth provisions governing the interface between multiple T&S operators and systems at present[116]. The Network Code indicates this will change, but there will not be a push to develop this area until projects with multiple T&S operators are announced. For T&S networks which are the responsibility of multiple entities, the UK Government requests a 'cluster leader' is selected, which will either be the entity primarily responsible for the network, or the entity nominated to liaise with the Government where required[117].

In the case of outages, insurance will play a role for the T&S operator. The UK Government anticipates that (subject to the results of the consultation mentioned at the beginning of section *4.3.2.2* above, the T&S operator licence will dictate the T&S operator obtain insurance against "asset damage risks"[118], with

business interruption insurance covering any losses accrued during an outage. This provides a cost-effective solution and encourages development of the CCS insurance sector.

4.4.4. General contractual overview of other jurisdictions

4.4.4.1. Norway – Longship

The Northern Lights joint venture forms the T&S network of the Norwegian Government's CCS development project (Longship). Northern Lights differs notably from the Porthos terms and conditions and the UK draft contracts. Two such points of difference are, firstly, that Northern Lights will be the first open-source CO_2 T&S infrastructure in the world[119], and secondly that CO_2 will be transported by ship, as opposed to pipeline.

The two first phase capture projects in Longship, the Heidelberg Materials cement plant in Brevik and the waste to energy plant owned by Celsio in Oslo, are contractually separate from the Northern Lights project, but state aid contracts support all three sections of Longship and the Norwegian Government bears the full-chain risks arising from the interaction between the CO_2 emitters and Northern Lights projects[120]. This includes costs arising from failures to deliver or accept deliveries of CO_2[121]. Further full-chain coordination is facilitated by a state-owned project integrator enterprise (Gassnova), which sets up the overarching framework within which all three projects operate[122]. See Section 4.4.2 for further observations regarding value-chain risk.

The commercial structure of having a separate T&S project is to facilitate alignment with corporate cultures, which reduces the risk of disagreement at a contractual level and streamlines the relationships with subcontractors in each stage of the value chain, so emitters will be separated from the T&S operator's subcontractor relationships[123].

The state aid agreement provides the contractual basis for the operation of the T&S system, and is available publicly online[124]. From an operational perspective, Northern Lights' various stages of contract development – being initially a concept report[125] and front-end engineering report[126] – have anticipated a high level of automation in the T&S system[127]. It is unclear whether this automation will add any contractual complexities which differentiate it from other projects discussed herein. The concept report also accounts for the lowering of entry costs for new CO_2 suppliers by ship by creating standardised plans and ship sizes. If one ship experiences an unplanned outage or upset, the selected ship size offers the opportunity to maintain the supply and keep the 'milking route' functional, preventing full stoppage to the capture facility[128].

Northern Lights' first commercial T&S undertaking will take place in 2025[129], so this may present further contractual data availability when this project gains traction and more private sector parties become involved in this CCS chain.

4.4.4.2. APAC Region

Outside of Europe, there is not as established a presence of CCS hub development. However, jurisdictions such as Australia have several large projects on the horizon, such as CarbonNet[130], Bayu-Undan[131], and the rapidly developing Moomba project[132]. These projects are not yet at the stage of having any contractual data available. Projects in Australia have historically seen the emitter looking after the full value-chain, such as Gorgon[133], rather than a hub scenario. It is anticipated that in the coming years, Australian CCS projects will involve a greater number of stakeholders, and move away from the linear value-chain model. At this point, it may turn to other jurisdictions which have pursued CCS hubs, such as those in Europe, for guidance on how to proceed with modelling these projects contractually.

Other countries in the APAC region will soon become key points of future research as large-scale CCS is committed to by countries such as Japan and Indonesia. CCS regulation in Indonesia has recently been updated through the Minister of Energy and Mineral Resources Regulation No.2 2023 and the Presidential Regulation No.14/2024[134]. These regulations guide the future of CCS project structures and relationships between T&S operators, which will become more prevalent as Indonesia steps up its CCS plans and engages in cross-border bilateral cooperation agreements, for example with Singapore[135]. As this region turns to contract development, further research will be required and it would be beneficial for ambitious jurisdictions to have access to as much publicly available contract data as possible.

4.4.5. Highlighting the need for centralised organisation of CO_2 stream bookkeeping and flow measurements

The ability to measure the quality and quantity of CO_2 accurately which is being transported and stored is imperative at all stages of the CCS value chain, a point which is reinforced consistently in contracts between emitters and T&S operators. This cruciality derives from a multitude of reasons, including the need to ensure health and safety, control the CO_2 flow process, detect leakage, and verify CO_2 quantity for the purposes of emissions trading schemes, investor confidence and taxation[136].

There is a strong technical focus on the parts of available contract data which relate to CO_2 stream bookkeeping and flow measurements. These technical specifications can vary between regulatory, contractual and operational stages of CCS projects, and there may be differences between the measuring system requirements contained in contract, compared to that contained in regulation[137]. Regarding the need for centralised organisation, in scenarios of multiple users of single metering points, or where there is CO_2 flow that spans multiple phases, there is a risk of flow measurement inaccuracy[138]. To counteract this partially, utilisation of a single and stringent system of measuring has been suggested[139].

Regarding current approaches, certain large-scale projects will designate a specific company or contractor to ensure flow assurance, such as at Teesside in the UK's East Coast Cluster[140]. This utilisation of a specialised contractor across the value-chain ensures a consistent set of contractual obligations with regard to bookkeeping and flow measurements. Similarly, the project integrator in the Northern Lights project assists in facilitating CO_2 specifications and export rate discussions between actors in the CCS chain, again fostering consistency[141].

T&S contracts will contain specific CO_2 measuring and transfer requirements. In the case of Porthos, the T&S contract template contains a 'Measuring Manual' which directs emitters on how to measure both the quantity and quality of CO_2 captured[142]. The responsibility of the emitters to comply with these measurement obligations and flow specifications more generally under the contract extends to any third-party CO_2 that they have utilised (see 3.2 above regarding third-party CO_2)[143]. Emitters are also obligated to ensure their measuring systems and equipment comply with legislation and relevant standards[144]. This assists with setting a minimum standard for emitters to adhere to, together with the measuring requirements set out in the contract, however emitters are responsible for designing and constructing their own measuring systems under the contract, which creates divergences between emitters and decentralises the measuring process[145].

From a UK perspective, the Network Code sets out both general and specific CO_2 specifications for both the HyNet project and the East Coast Cluster[146]. It is intended that each of these projects will carry specific measurement requirements, however these are not yet specified within the contract template[147]. As with Porthos, emitters in the UK hubs will require to commission their own measuring equipment[148]. The T&S company will have oversight of the specifications of the equipment[149], which will

facilitate holding each emitter to a consistent project standard. It is anticipated that further measuring and CO_2 specification requirements for emitters will arise from the forthcoming T&S revenue support agreements[150].

At the time of writing this document, it is still unclear whether Northern Lights has a different measuring system. It appears that the measurement-specific information is contained in appendices that are not available online in any language. Unlike Porthos and the UK hubs, Aramis presents a broader range of emitters and the transport of CO_2 by both pipeline and non-pipeline methods. The risks arising from decentralised CO_2 measurement and bookkeeping will therefore likely be greater and require careful contractual navigation.

Overall, CCS projects would benefit from a standardised measurement system for CO_2 flow, particularly in scenarios of multiple emitters or storage operators. A lack of centralisation or coordination in this area could result in measurement inconsistencies, which pose a high risk for emitters and T&S operators alike.

4.5. Commercial Models and Partnerships

4.5.1. Multi-stakeholder partnerships for CCS

While the maturity of CCS regulation varies across different regions, as discussed earlier, the economics of CCS remain the most widely cited challenge to deployment regardless of jurisdiction. By definition, CCS is a technology that has no intrinsic economic value but one that incurs high capital and operational costs. These costs – especially the significant upfront capital outlay – remain prohibitively high for most industries and operators to absorb on their own. Indeed, the significance of CCS's high costs cannot be stressed enough particularly as the technology has a well-documented track record of project delays and budget overruns[d].

It is not surprising then that most existing CCS projects have leveraged on a degree of public support with governments involved in some form and to a certain extent, at least at early stages of project development. On one end of the spectrum, government intervention can be minimal and limited to establishing commercial incentives and/or penalties to spur private investment: these can include grants and tax credits, or taxes for non-compliance. The US, Canada and the EU are examples of this approach. On the other end of the spectrum, governments can retain full control over projects where state-owned or national oil companies invest in and operate entire projects. Examples of this model include China, Saudi Arabia, Qatar and UAE. In other cases, risks can be shared between government and the private sector where the government's role is limited to regulating specific aspects or parts of the CCS supply chain, while also playing a central role in coordinating activities. The UK, Norway and Denmark are examples of this hybrid approach.

CCS projects have also often been underpinned by multi-stakeholder partnerships, including between private and public bodies (public-private partnerships – PPPs). This is in part due to the need along the CCS value chain for a broad range of technical expertise but also to cater to investors and developers with different risk appetites and long-term interests. For instance, PPPs help leverage the governments' regulatory expertise and the technological know-how that often only the private sector can offer, which can in turn help drive innovation. Innovation can either occur at early stages by supporting research and development of CCS technologies through funding and establishing dedicated research facilities, or by

[d] For instance, in the US, the Kemper CCS project saw cost overruns of around $4billion, while most recently the Klemestrud waste-to-energy CCS project in Norway was halted for a year after projections of capital cost overruns.

helping to deploy and demonstrate actual projects through regulatory support; this ultimately fosters long-term collaboration and knowledge sharing between different stakeholders.

Involvement of different stakeholders in CCS projects is particularly evident, and necessary, for the T&S segment of the value chain which, much like water and gas networks, is considered a common good and serves a number of actors. In its simplest form, a T&S business model will include at least one emitter from which CO_2 is sourced, an operator who builds and/or maintains the transport and/or storage infrastructure, and a regulatory body. Variations of this model can exist with multiple CO_2 emitters and/or operators involved, as discussed below. It is thus natural that existing commercial-scale CCS projects – as few as they may be today – have exhibited distinct capital and ownership structures, backed by various financial incentives depending on the commercial framework they operate within (e.g. carbon taxation, tax credits, emissions trading, and/or carbon contract-for-difference schemes).

4.5.2. CCS business models

While CCS projects can be privately and/or publicly owned, projects can also be broadly categorised into 'full-chain' and 'part-chain'. Most projects to date have adopted the full-chain approach where T&S is handled by the same entity capturing CO_2 at source, and where operations are vertically integrated. This model is typical of EOR-coupled projects where a company controls and manages the entire project from its emission source(s) to storage/utilization site. In contrast, T&S can be operated independently from the capture segment. Examples of full-chain models include the Sleipner and Snøhvit projects in Norway and the Quest project in Canada, while part-chain models include the Northern Lights (Norway) and Porthos (Netherlands) projects as discussed earlier.

The setup of a given project reflects whether cross-chain risks may arise and how they may impact the viability of the project: these risks can be higher the more actors that are involved but ones that can be alleviated through different approaches. For instance, in a full-chain model, operations are highly streamlined and thus coordination risks across the chain are effectively avoided. While a plus, only a few entities would possess the expertise necessary to operate entire CCS chains. Moreover, this model risks creating monopolistic behaviour and not allowing for natural competition and an open access network, which can in turn hinder scalability of the technology beyond those projects.

In contrast, by splitting the value chain into its different segments, a part-chain model could help allocate responsibility to specialised entities who are best placed to handle it. This is particularly the case where industrial emitters may not possess the technical know-how to capture and/or transport/store CO_2 (e.g. for steelmakers where CO_2 capture is not inherent to the steelmaking process). Moreover, the skillset to transport and store CO_2 lies predominately in the oil and gas industry whereas CO_2 will need to be captured from industrial emission sources with different technical characteristics and standards. Another variation is separation of the CO_2 collection hub from its transport segment which adds another stage along the value chain – and potentially an additional stakeholder (an aggregator) – and hence logistical complexity to the model. Such an approach best serves regions where CO_2 is collected domestically for eventual export across borders (e.g. Germany to the North Sea). Here, an aggregator can build and operate the aggregation infrastructure while negotiating separate offtake agreements with emitter(s), transporter(s) and storage operator(s).

It is therefore evident that, depending on the technical, geographical and political context, a value chain split may not only be preferrable but necessary. Perhaps more critically, a part-chain, non-linear model offers a strategic advantage by allowing for future expansion of the network where new entrants can connect to established projects as part of CCS clusters/hubs. This also means that a trade-off may

emerge between the need to streamline operations amongst fewer actors (as in full-chain, linear models) and the potential for eventual scalability of operations.

To alleviate integration risks in part-chain models, governments can intervene and play an intermediary role to coordinate activities amongst their corresponding stakeholders and establish a commercial framework with stable revenue streams for each participant. Fundamentally, this helps address potential misalignment between FID/commencement dates of capture versus T&S projects, which avoids the 'chicken and egg' paradox that has long been a deterrent of private investment in CCS: where CO_2 capturing entities fear that storage sites may not be available for its offtake, or stores may indeed be developed but CO_2 does not flow through the pipeline.

A prime example of this is the Norwegian Government's approach to CCS development, as noted in Section 4.3.4. Norway established the state-owned enterprise, Gassnova, to play the project integrator's role for its Longship project. Through state aid agreements, the different segments of Longship including its T&S component (Northern Lights) and the first emitters (Brevik CCS and Celsio) receive generous government funding which provides cost assurance by covering part of the capital and operational expenses of the different industrial partners, up to a pre-determined maximum level. This financial support aims to supplement the EU-ETS price, assuming emitters are subject to it and where they stand to benefit from potentially reduced ETS quota costs. The government also takes on risks of delay whereby if either the capture or T&S component of the project is not ready in time, it compensates the other party. Moreover, industrial partners retain full ownership of the facilities and enjoy special network access benefits: for instance, Brevik and Celsio incur no T&S costs for the first ten years of Northern Lights' operation, while Northern Lights receives spare capacity in the T&S infrastructure to support business development and future expansion[151].

Specifically, Northern Lights aims to expand its current capacity (of up to 1.5 Mtpa) to 5-7 Mtpa to cater to a rising demand for transport and storage services from emitters in neighbouring countries – evidenced by the increasing number of bilateral transboundary agreements as highlighted in earlier sections. As such, the business case for Northern Lights in the future should become less dependent on government funding and more so on revenues generated from tariffs paid by commercial customers from across Europe. There is also a profit-sharing mechanism in place whereby if Northern Lights becomes profitable over time, the Government will take a share of the profits, from 50% rising to 75% at defined thresholds[151]. The Norwegian Government's approach is also an example of how government can help de-risk projects by bearing some of the long-term liabilities associated with CO_2 storage until a self-sustaining CCS market is in place. In the Northern Lights' case, the government assumes partial liability for leakage from the storage subsurface complex.

Elsewhere, T&S infrastructure is increasingly planned and commissioned around existing or evolving industrial clusters, where one or more CCS hubs can ultimately arise. Where a T&S model involves a single hub, operations are usually undertaken by one entity – or a consortium of companies that can include state-owned enterprises – forming a natural monopoly and hence necessitating regulation of service fees. Case in point, a regulated asset base (RAB) model is adopted for T&S infrastructure development around the UK clusters, where an economic regulator (Ofgem, in this case) dictates the level of allowed revenue that an operator can generate to cover its costs plus a reasonable return on investment, based on pre-defined parameters. Under the UK TRI (T&S Regulatory Investment) model, operators recoup investment through fees charged to users of the network (connected emitters), backed by a government support package which, akin to the Norwegian approach, guarantees operators income

in case of shortfall between allowed revenue and that generated from network user tariffs, i.e., if enough emitters are not connected in time.

In a more directly involved manner, governments can also take equity in T&S infrastructure in return for capital contribution, as is the case in Denmark. In the Danish case, the state company Nordsøfonden takes a 20% interest in all future CO_2 storage licences while sharing costs and de-risking investment for private investors at early stages of project development. Through state ownership, this model can help unlock cheaper capital for private investors, further lowering financial risks for developers, and potentially translating to lower network tariffs to end-users.

Under the least regulated – or 'free market' – model, a government can have little-to-no intervention in T&S development except for overseeing environmental compliance. This model promotes open competition amongst operators where users have the option to choose between a variety of T&S service offerings. It also allows for many entrants along different parts of the value chain (e.g. transport companies, storage operators, aggregators), which may admittedly increase complexity as operators need to negotiate contractual terms with emitters on an individual basis. It is worth noting that while there is no direct subsidy from government for constructing the T&S infrastructure itself in this model, the government can support its operation indirectly through financial incentives provided for emitters, part of which is passed on to the T&S operator as service fees. This is the US approach towards T&S development, supported by 45Q tax credits paid to capturing entities. As an example, the Denbury T&S project which was recently acquired by ExxonMobil aims to connect industrial emitters to Denbury-owned and operated storage sites, in return for service fees. Note here that fees may not be regulated as in previous models, however it is expected that open-market competition would create an incentive to offer T&S services at the lowest cost possible.

5. Discussion

5.1 System availability relates to system flexibility

Variability in CO_2 supply and composition from industrial sources can pose operational challenges to a system's availability. Since there will likely be flow uncertainties, system availability relates to system flexibility. An important knowledge gap was identified in the level of CO_2 supply variability from emitters, which will likely be sector dependent (e.g. seasonal variations in power plants). To deal with the topic of CO_2 composition, the need for developing standards for CO_2 composition is widely recognised, and many initiatives are being undertaken both nationally and internationally (e.g. ISO, CEN, etc.). In a broader sense, accurate and centralised CO_2 monitoring and verification systems are essential across the CCS value chain to ensure compliance with (regulatory) standards, optimise flow management, and maintain integrity in CO_2 bookkeeping. This will be increasingly important as CCS develops into an international market.

In order to accommodate variability of CO_2 supply, system flexibility can be increased through design options. On a network level, buffering techniques such as temporary storage facilities or linepack can provide flexibility to CO_2 supply variations in the order of days and hours, respectively, depending on the severity of fluctuations in the supply rate. However, Rycroft et al. (2022)[1] stated that installing quayside tanks to provide resilience to CO_2 supply rate variability for a couple of days will likely be prohibitively expensive. A project-specific assessment is required to weigh the incurred costs against the improvement in flexibility of the transport and storage network.

Resilience to variability in CO_2 supply can also be incorporated in the design of a T&S system such that it has a broad and continuous operational envelope, without uninjectable rates or preferably even without unique injection configurations for a given supply rate. In this sense, system flexibility and resilience to variability is closely tied to the operational performance and flexibility of injection wells, which is for a large part determined by reservoir conditions such as reservoir pressure and injectivity. Wells in depleted fields often present less flexibility compared to those in saline aquifers due to larger pressure contrasts. To add flexibility and increase the size of the operational window at the well level, engineering options include insulation of the transport pipeline, the choice of completion size, using tapered tubing, downhole chokes and injection CO_2 in gas phase. However, many of these options incur costs, through network construction and operation or by decreasing the maximum flow rate. Again, a project-specific trade-off is required between the improved flexibility in the operational window of the injection system (and resilience to variability) and increased cost of network construction and operations. Again, it is important to recognise that the reservoir conditions play a dominant role in the operational window of injection wells and therefore there is not a one-size-fits-all injection strategy for CO_2 injection.

Other important factors in the availability of a transport and storage network for CO_2 are the performance and stability of the compressor stations and the injection wells. The risk of downtime of the system due to failure at either of these elements can be mitigated by installing overcapacity or redundancy in the system, however, these always pose a trade-off between risk mitigation and extra costs. The positive Final Investment Decision on the Porthos project demonstrates that a spare compressor station and a spare injection well can be economically feasible. In the case of a T&S project relying on a single trunkline or backbone to transport from CO_2 from a collection point to multiple storage locations without rerouting options, installing a redundant infrastructure will likely be prohibitively expensive, leaving a trunkline to be a critical element, although outage of such an element is not expected to be likely.

With a multitude of CO_2 injection projects into depleted fields and saline aquifers in the planning stage, the coming decade is expected to yield a rich body of operational experience. For depleted fields, experience of management of the pressure difference between the transport system and the reservoir and the undesired effects this can produce, such as hydrate formation, two-phase flow or low temperatures in the system are valuable. Particularly high injectivity wells can be operationally challenging because they often have high minimum flow rates constrained by downhole and wellhead temperature restrictions. Conversely, lower-quality wells, while operationally simpler, have lower flow rates and more wells are needed to achieve a certain target injection rate. A challenge could arise when tying a depleted field with a low reservoir pressure and high injectivity to a network operating in dense phase. In such a situation there could be a mismatch between the operating conditions of the network and the needs for injection at the well. To avoid this, project developers planning on constructing infrastructure with overcapacity should have a forward look towards storage locations eligible for tie-in and prepare a suitable strategy to realise the corresponding operating conditions for the occasion, where the aim must be to maintain overall injection capacity.

While appropriate engineering can mitigate risks to downtime to a certain extent, unplanned outages remain inherently unpredictable and to some extent, time will tell what availability rates are achievable. However, in this rapidly evolving industry, it is important that knowledge gained by the early projects is shared in order to make full use of the experience and help speed up the development and reinforce other projects. The coming few years are crucial when it comes to sharing lessons learned on outages of a T&S systems, planned or unplanned, as well as best practices on dealing with issues that may lead to outage, are publicised and shared.

5.2 Optimisation of network conditions

The CCS industry is rapidly gaining momentum and is evolving in the direction of large integrated multi-user networks. These large-scale integrated multi-user value chains will include shipping terminals or pipeline inlets, and will thus collect CO_2 from emitters, condition to the applicable standards to finally be transported to a storage location in the form of a depleted field or a saline aquifer. Early projects may grow by adding users (emitters or storage operators) to the infrastructure.

In order to leverage synergy between the parties collectively tied into a network, optimisation of the operating conditions is required from a technical perspective and, as a result, from a commercial and contractual perspective. In complex networks, injection wells with differing operational bandwidths will likely coexist. The performance of a T&S network is strongly influenced by the "worst" operating well (array) or well. The operating pressure in the backbone necessary for one well may be detrimental to the other. Here, optimising from a network perspective, rather than focusing on individual wells or well arrays, is advisable to minimise overall costs and enhance system flexibility and resilience. The operating pressure in the transport pipeline can be the minimum required pressure to inject the overall supplied rates, rather than having pipeline pressure as dictated by a single well (array). However, when a T&S network is used by multiple storage operators, there may be commercial implications when flow rates for some wells are lower than the maximum technically viable; such an approach may require contracts different from those currently proposed.

In addition, a network-based approach of setting operating conditions allows for better accommodation of upsets in the system or an oversupply of CO_2. In case of well failure in the network, which can occur due to many reasons and has happened in the past (for example in the Norwegian project Snøhvit, in which the injection well was connected to a new injection horizon), the total storage rate capacity of the network does not have to be affected when there is a possibility for distribution of excess flow across

other wells in the network. Contractual complexities arise in multi-user CCS projects due to the interaction between multiple emitters, transports, and storage operators. These challenges are particularly significant in aforementioned areas such as outage management, capacity distribution, and ownership dynamics. Standardised contractual frameworks and centralised bookkeeping could help mitigate some of these challenges. The UK serves as an example here, where the T&S operators can deploy certain capacity optimisation principles which, in a non-discriminatory fashion, allows for redistribution of capacity whilst maximising the number of constrained users it is providing availability to in these circumstances.

5.3 Regulatory Considerations

In the development of T&S infrastructure, regional regulatory approaches have significant impact. For instance, the European Union (EU) has a stringent and detailed regulatory framework focused on environmental protection and financial security for CCS projects. In contrast, North America has currently adopted a more flexible, deal-making approach. Another notable difference is that Enhanced Oil Recovery (EOR) is important for funding CCS in North America, where CO_2 is used to extract additional oil, indirectly supporting CO_2 storage. However, integrating EOR with CCS in the EU faces regulatory limitations, indicating a need for regulatory adjustments to better exploit this synergy.

Public-private partnerships (PPPs) and government involvement can play a significant role in advancing CCS projects. Government involvement, where appropriate, may provide regulatory and financial support to help de-risk projects and attract private investment. To support the development of the CCS industry, several regulatory measures could be considered. One area where governments might intervene is in creating a more favourable insurance market for CO_2 transport. This could involve measures such as subsidies or guarantees to insurers, aimed at reducing premiums and encouraging broader market participation. By improving the accessibility and affordability of insurance, governments could help mitigate some of the financial risks associated with CO_2 transport, potentially promoting greater industry participation.

Secondly, governments should streamline permitting processes by enhancing regulatory clarity and support capacity. This would require adequately resourced permitting bodies with dedicated personnel for processing CCS permit applications. There is a need for simplified and fast-tracking permitting procedures, to reduce administrative delays.

For publicly funded projects, third party access should be guaranteed to foster collaboration and maximise the use of the network. The adoption of a common carrier model for CO_2 pipelines is encouraged for CO_2. This would ensure that third-party users can access transport networks under non-discriminatory terms. Full-chain models, whilst able to streamline operations, risk monopolistic behaviour. This contrasts to part-chain models, which promote specialisation and scalability through open-access networks.

One challenge still faced by T&S project developers is the high capital expenditure of transport and storage projects. Carbon markets, particularly compliance markets like the EU Emissions Trading System (EU-ETS), provide an economic incentive to emitters for emission reductions. However, current carbon pricing levels and their complexity when applied to cross-border projects limit their effectiveness. A measure to improve the effectiveness of the EU-ETS and ensure a more holistic approach is to expand its coverage to include all modes of CO_2 transport (ships, pipelines, rail, and road). In addition, agreements should be developed between the EU and other ETS schemes, such as the UK ETS, to ensure mutual recognition of CO_2 storage and allow cooperation across the EU-UK border. This would involve

standardizing metering and verification processes and ensuring that emissions reductions are correctly accounted for and deducted from the capturing entity's liabilities.

5.4 Towards an international CCS market

Currently, the international landscape for CO_2 storage and transport is highly diverse, with varying regulations across regions. Although the first cross-border projects are starting to develop in Europe, with recently the first CO_2 cross-border demonstrations, cross-border CO_2 transport still faces significant legal and logistical challenges Frameworks such as the London Protocol, the OSPAR Convention, and various national regulations create a complex patchwork of rules. The slow ratification of critical amendments, such as the London Protocol's Article 6 amendment on CO_2 export, hinders the progress of international T&S projects.

Inconsistent regulatory frameworks between countries and difficulties in aligning liability regimes for pipeline versus shipping transport add to the complexity of cross-border movement of CO_2 for permanent geological storage. Currently, bilateral agreements are a primary tool for overcoming some these barriers, examples of which we have seen between European Union Member States such as Denmark, The Netherlands, Norway, Belgium and Sweden. Harmonisation of liability frameworks is needed through the development of standardised international guidelines for CO_2 transport liability that align with disparate national and international regulations. This could involve adopting elements from the LLMC and applying them to pipeline transport to ensure consistent liability limits and conditions. Harmonising liability frameworks would provide greater certainty for companies involved in CO_2 transport, reducing the risks associated with cross-border projects. This will have to include CO_2 ownership transfer guidelines. These guidelines should specify the points at which ownership (and thus liability) is transferred, as well as the standards for CO_2 purity and the tracking of transported quantities. Such clarity would reduce uncertainties and potential disputes between transport operators and storage facilities, ensuring smoother cross-border CO_2 transport operations.

6. Conclusion

The development and expansion of CO_2 pipeline infrastructure is crucial for the success of carbon capture and storage (CCS) initiatives worldwide and for reaching the Paris climate target.

Because outage of a transport or storage system has potential financial, technical and social consequences, it is key that the developing CCS projects prove to be reliable in the sense that downtime is minimized, particularly unplanned downtime. This study has reviewed what elements make up availability of a CO_2 transport and storage system, provides an overview of current projects and examines regulatory approaches in a growing CCS industry.

Currently, the US has the largest share of CO_2 infrastructure worldwide, with more than 8,000 km of pipelines transporting approximately 70 Mtpa of CO_2 annually, primarily for enhanced oil recovery (EOR). Canada and Norway have significant transport and storage networks, focused on EOR and natural gas sweetening. Meanwhile, more CCS projects dedicated to emission reduction purposes are arising and advancing. Complex networks will form, especially when some of the existing hurdles for cross-border transport and storage of CO_2 are removed. In particular, European countries are making efforts to integrate multiple CO_2 sources and sinks into a flexible multi-user open-access network. In emerging markets like China and the Middle East and North Africa (MENA) region, the lack of comprehensive CCS-specific regulations and reliance on existing environmental laws pose challenges and may inhibit progress. However, these regions are showing increasing interest in CCS to meet climate commitments, suggesting potential for regulatory evolution and greater CCS adoption in the future.

The expected availability of CO_2 pipeline-based T&S networks can be high, upwards of 95%. Scheduled maintenance is typically limited to several days per year. In future multi-user projects, like Porthos, maintenance is coordinated along the entire value chain to minimize downtime and well shut-ins. CCS systems using ships transporting CO_2 are expected to have similar availability rates. Weather conditions are the primary factor in system availability in such case. One of the factors that make up the overall availability of a T&S network is its resilience to upsets along the chain. Built-in redundancy or buffering storage are examples of measures to increase resilience to outages along the chain. Variability in both CO_2 supply and composition from industrial sources can influence network availability by posing operational challenges. Injection wells have an operational window which is for a large part dictated by reservoir conditions, yet flexibility can be added through engineering solutions such as insulating (parts of) the pipeline infrastructure, placing downhole chokes and tubing size. The deployment of technical solutions to add resilience or flexibility to a T&S system is dependent on the trade-off between risk mitigation and costs (which could be in the form of a reduced flow rate).

CCS networks will likely evolve to be increasingly complex large-scale integrated networks connecting multiple emitters to multiple storage locations. As a result of this added size and complexity, these networks may be inherently more flexible. However, as each injection well tends to have its own specific injection window (resulting from the storage reservoir conditions and the design of the well), this means that optimization of the operating conditions should also be performed from a network perspective rather than from the perspective of an individual well or injection site. Here, a need arises for standardized contractual frameworks for multiple users sharing a network, covering optimization of network operating conditions and includes centralized bookkeeping. Optimization on a network level rather than a hub or well level can save costs while also providing opportunities for the redistribution of excess flow. Hence, standardized contractual frameworks are recommended to include the commercial aspect of flow redistribution and flow optimization in the case of outages along the chain. Although

there is a notable lack of contractual attention on CO_2 distribution during outages, the UK means to streamline interaction in such as a case through certain “capacity optimization principles”. It is not confirmed if this approach is followed in other jurisdictions.

The development of CCS infrastructure is heavily influenced by regional regulatory approaches. To advance CCS as a whole, governments are recommended to make efforts on harmonizing regulatory frameworks between countries as well as standardizing guidelines (e.g. on liabilities, CO_2 ownership, CO_2 composition, emission trading schemes etc.), streamline permitting processes, and enhance insurance markets for CO_2 transport. This will contribute to establishing cross-border projects.

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Section 1

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Section 5

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Appendix – Existing CO_2 pipelines.

Table 6. Overview of the existing CO_2 pipelines in the US. Info from these sources:

Pipeline Name	Operator	Length (km)	Route	Operation year	Status	Purpose	CO2 Source	Pipe Diameter (inches)	Capacity (MMCFD)	Operational Pressure (psi)
Beaver Creek Pipeline	ExxonMobil (Denbury)	74	WY Wind River Basin properties	2008	Operational	EOR	Captured CO2 from gas processing	8	NA	NA
BP's CO2 Pipelines	BP	NA	Various future routes planned for CCS	NA	Proposed	CCS	Captured CO2 from various sources	NA	NA	NA
Bravo Pipeline	Kinder Morgan	351	Bravo Dome, NM to Denver City, TX	NA	Operational	EOR	Natural CO2 source (Bravo Dome)	20	382	1800-1900
Canyon Reef Carriers Pipeline	Kinder Morgan	225	Denver City, TX to Snyder, TX	1972	Operational	EOR	Natural CO2 source	16	270	2000
Cedar Creek Anticline Pipeline	ExxonMobil (Denbury)	214	Bell Creek Field, MT to Cedar Creek Anticline	2022	Operational	EOR	Natural CO2 source	16	NA	1200-2200
Centerline Pipeline	Kinder Morgan	182	Denver City, Texas to Snyder, Texas	NA	Operational	EOR	Natural CO2 source	16	230	NA
Central Basin Pipeline	Kinder Morgan	225	Denver City, TX to Snyder, TX	NA	Operational	EOR	Natural CO2 source	26	600	1800
Chevron's CO2 Pipelines	Chevron	NA	Various routes in California and Colorado	NA	Operational	EOR	Natural and captured CO2 sources	NA	NA	NA
Coffeyville Pipeline	Canvas Energy (Chaparral Ene	109	Coffeyville, KS to oil fields in OK	2013	Operational	EOR	Captured CO2 from fertilizer production	8	80	2000
Cortez Pipeline	Kinder Morgan	808	McElmo Dome, CO to Denver City, TX	1984	Operational	EOR	Natural CO2 source (McElmo Dome)	30	1500	1450
Delta Pipeline	ExxonMobil (Denbury)	179	Jackson Dome CO2 source to Delhi Field, LA	2009	Operational	EOR	Natural CO2 source (Jackson Dome)	24	NA	NA
Eastern Shelf Pipeline	Kinder Morgan	146	Near Snyder, TX to West of Knox City, TX	NA	Operational	EOR	NA	NA	NA	NA
Free State Pipeline	ExxonMobil (Denbury)	146	Jackson Dome CO2 source to West Yellow Creek, MS	2005	Operational	EOR	Natural CO2 source (Jackson Dome)	20	NA	NA
Green Pipeline	ExxonMobil (Denbury)	515	Donaldsonville, LA to Hastings Field, TX	2010	Operational	EOR	Captured CO2 from industrial sources (e.g., Port Arthur, TX)	24	NA	1200-2220
Greencore Pipeline	ExxonMobil (Denbury)	373	Lost Cabin gas plant in WY to Bell Creek Field, MT	2012	Operational	EOR	Captured CO2 from gas processing	20	NA	2220
Illinois Industrial CCS	Archer Daniels Midland	2	Decatur, IL to nearby geological storage site	2016	Operational	CCS	Captured CO2 from ethanol production	8	NA	NA
Navigator CO2 Ventures	Navigator CO2 Ventures	2092	IL, IA, MN, NE, SD	NA	Canceled	CCS	Captured CO2 from ethanol plants	NA	NA	NA
NEJD Pipeline	ExxonMobil (Denbury)	295	Jackson Dome CO2 source to Green Pipeline connection	1986	Operational	EOR	Natural CO2 source (Jackson Dome)	20	NA	NA
Occidental's CO2 Pipelines	Occidental	4023	Various routes in Permian Basin	NA	Operational	EOR	Natural and captured CO2 sources	NA	NA	NA
Pecos Pipeline	Kinder Morgan	NA	McCamey, TX to Iraan, TX	NA	Operational	EOR	NA	NA	NA	NA
Petra Nova Pipeline	NRG Energy/JX Nippon	129	Near Houston, TX to West Ranch oil field	NA	Operational	EOR	Captured CO2 from coal-fired power plant	NA	NA	NA
Sheep Mountain Pipeline	Kinder Morgan	660	Sheep Mountain, CO to Snyder, TX	NA	Operational	EOR	Natural CO2 source (Sheep Mountain)	24	NA	2000
Souris Valley pipeline	Dakota Gasification Company	322	Beulah, ND to Weyburn, Saskatchewan, Canada	NA	Operational	EOR	Captured CO2 from synthetic natural gas production	14	NA	2000
Summit Carbon Solutions	Summit Carbon Solutions	3219	Across IA, MN, NE, ND, and SD	NA	Proposed	CCS	Captured CO2 from ethanol plants	NA	NA	NA
Tallgrass Energy	Tallgrass Energy	631	Converts natural gas pipeline from NE through CO to WY	NA	Approved	CCS	Captured CO2 from ethanol facilities	16	NA	NA
West Gwinville Pipeline	ExxonMobil (Denbury)	82	NEJD Pipeline to Cranfield Field	2008	Operational	EOR	Natural CO2 source	18	NA	NA
Wolf Carbon Solutions	Wolf Carbon Solutions	451	IA to IL	NA	Proposed	CCS	Captured CO2 from electric cogeneration and ethanol plants	NA	NA	NA

Table 7. Overview of the existing CO_2 pipelines in Canada.

Pipeline Name	Operator	Length (km)	Route	Operation year	Status	Purpose	CO2 Source
Souris Valley Pipeline	Whitecap Resources	61	Canada - U.S. Border to Weyburn, SK	2000	Operational	EOR	Captured CO2 from synthetic natural gas production
Cardinal Energy Midale CO2 pipeline	Cardinal Resources Ltd	25	Receives CO2 from the Souris Valley pipeline and transports	2005	Operational	EOR	
Bounday Dam To Weyburn CO2 Pipeline	SaskPower, Whitecap Resources	74	Boundary Dam Power Plant, SK, to Weyburn, SK	2014	Operational	CCS and EOR	
Quest	Shell Canada	64	Scotford Upgrader, AB, to Thornhill, AB	2015	Operational	CCS	Captured CO2 from a bitumen upgrading unit
Alberta Carbon Trunk Line (ACTL)	Wolf Midstream	240	Sturgeon County, AB, to Lacombe, AB	2020	Operational	CCS and EOR	

Table 8. Overview of the existing CO_2 pipelines in Norway.

Pipeline N	Operator	Length (miles)	Length (km)	Route	Operation year	Status	Purpose	CO2 Source
Snøhvit	Equinor	95	143	LNG terminal at Hammerfest to the Stø formation	2008	Operational	CCS	Captured CO2 from gas processing

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Energy & Materials Transition

Princetonlaan 6
3584 CB Utrecht
www.tno.nl

TNO innovation for life

IEAGHG

ieaghg.org
+44 (0)1242 802911
mail@ieaghg.org

IEAGHG, Pure Offices, Cheltenham Office Park,
Hatherley Lane, Cheltenham, GL51 6SH, UK

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