Briefing on Operational Flexibility for CO_2 Transport and Storage

2nd Report of the Thematic Working Group on:

CO_2 Transport, Storage, and Networks

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About the CCUS Projects Network

The CCUS Projects Network comprises and supports major industrial projects underway across Europe in the field of carbon capture and storage (CCS) and carbon capture and utilisation (CCU). Our Network aims to speed up delivery of these technologies, which the European Commission recognises as crucial to achieving 2050 climate targets. By sharing knowledge and learning from each other, our project members will drive forward the delivery and deployment of CCS and CCU, enabling Europe's member states to reduce emissions from industry, electricity, transport and heat.

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Executive summary

The CO_2 stream produced during a capture project can vary in mass rate and composition during a carbon capture and storage (CCS) project's lifetime. For larger CCS projects with numerous capture sources the potential variability can sometimes be substantial. Transport and storage networks must therefore be designed to incorporate some of this flexibility into their operations and be able to handle varying flow rate and composition of CO_2 stream.

The impact that changes in CO_2 flow rate or composition can have on transport and storage processes has been assessed in previous research. This has included research to assess the impact that temperatures, pressures and chemical changes induced within the pipelines, wells and storage reservoir may have. The resulting knowledge developed from these studies has allowed CO_2 transport and storage projects to assess the risks associated with varying flow rates and compositions and incorporate flexibility into projects to mitigate some of these risks. This report therefore focuses on how European projects currently under development are managing flexibility within their operations.

This report aims to provide an insight into how CCS projects are developing their operational plans and incorporating flexibility into their management systems. It focuses on two specific case studies: The Northern Lights project in Norway and the Porthos project in the Netherlands.

Overall, projects tend to be moving towards plans that involve numerous capture sources which lead to one shared transport and storage infrastructure network. Northern Lights especially has decoupled the capture site processes from the transport and storage network, with CO_2 sites located across Norway and potentially across Europe. Porthos has all sites located in the Port of Rotterdam but has also allowed for more network flexibility by incorporating numerous sources, from the same area. This design reduces the operational risk in comparison to relying on the output from one capture source. Temporary storage along the chain, for example as planned within the Northern Lights project, will also reduce the risk of experiencing changes in flow rate as it incorporates the ability to buffer CO_2 quantities between capture and storage.

Differences in CO_2 composition from different capture sources is often addressed by designing one specification to which all capture sources must adhere. This means that compositional variation does not have to be accommodated during transport and storage operations (the CCUS Network's 1st thematic report on CO_2 specifications gives further details). For Northern Lights, the CO_2 specifications that capture sites must adhere to are driven by the shipping standard's requirements. Coincidentally, the shipping requirements also fulfil and exceed those required for pipeline transport and storage. Therefore, ensuring that CO_2 specifications also meet pipeline and storage requirements is not an issue.

This report concludes by highlighting how future research projects, especially pilot demonstration CCS projects, can contribute to the current knowledge gaps regarding operational flexibility.

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Table of Contents

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Briefing on the Operational Flexibility for CO_2 Transport and Storage

1 Introduction

This report follows discussions at the CCUS Projects Network's third knowledge-sharing event for members, held in Brussels on 23rd January 2020. Discussions in the thematic working group on CO_2 transport, storage, and networks focused on operational flexibility with Northern Lights presenting how their project has been developed with a new conceptual approach to handling operational flexibility for full CCS chain development.

The CO_2 stream produced can vary in flow rate and composition during a capture project's lifetime. For larger CCS projects with numerous capture sources the potential variability can sometimes be substantial. Transport and storage networks must therefore be designed to incorporate some of this flexibility and be able to handle varying flow rates and composition of the CO_2 stream.

The impact that changes in CO_2 flow rate can have has been assessed in previous research[1], which has assessed the temperature, pressure and chemical changes induced within the pipelines, wells and storage reservoir at different flow rates. This report will therefore review how projects are managing flexibility within their operations.

1.1 Objective and scope

The aim of this report is to outline the concept of operational flexibility and investigate how CCS projects are currently incorporating flexibility into their CO_2 transport and storage networks. Two case studies are provided in this report: one on the new concept designed by the Northern Lights project (as presented at the third knowledge-sharing event) and a second on the Porthos project, to study the two different approaches that have been designed to manage flexibility within operational requirements.

At the CCUS Project Network's second knowledge sharing event members also discussed the role of pilot projects in developing further knowledge on operational flexibility. Given the single source to single point nature of many pilot CCS projects the question was raised of how the research being conducted can contribute towards developing greater flexibility in future projects which are likely to be more complex in nature. The role of future research is therefore discussed in Section 5 of this report.

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[1] An extensive review was undertaken by (IEAGHG, 2016) and (Wetenhall et al., 2017).

1.2 Report structure

This report consists of six main sections. Firstly an introduction, then the second section gives an overview of the concept of operational flexibility. Then the third and fourth sections are the case studies on the Northern Lights project in Norway and the Porthos project in the Netherlands. These two sections provide an insight into how these two projects are handling flexibility and the operational differences within the projects that have led to these different approaches.

Section five highlights the future research needs that are required for CCS projects to be able to develop effective operational plans that can incorporate the flexibility required most effectively. And the report ends with conclusions.

2 Operational Flexibility

2.1 Definition of Flexibility

Flexibility is defined as a project's ability to accommodate changes in CO_2 stream, both in the amount of CO_2 (the flow rate) but also its composition. Numerous European CCS projects are currently developing plans to transport and permanently store large quantities of captured CO_2. Depending on the project, these CCS operations are likely to include the transport and storage of CO_2 from more than one source. This can lead to a varying CO_2 stream mainly in the volume of CO_2 being produced but also its composition.

A variation in flow rate and/or a change in composition is likely to negatively impact a project as it will lead to changes in pressure, volume and chemistry which may impact the integrity of pipelines or result in changes of flow within the reservoir. Therefore, in order to accommodate this change and prevent a change in flow, transport and storage operations will have to be flexible and be able to accommodate these changes somewhere within the CCS chain. The potential operational challenges posed by changes in flow rate or CO_2 stream composition are outlined below.

2.2 Impact of Changes in CO_2 Stream Composition

Although capture sources are able to produce relatively pure CO_2 streams (up to 99.7% CO_2), different capture techniques and sources of CO_2 can lead to different compositions and quantities of impurities in the stream. For larger CCUS projects numerous capture projects are likely to be utilised leading to a variety of capture sources entering a single transport and storage in network. This can lead to a variation in the stream composition throughout a project's operational lifetime.

Impurities (particularly water and dioxygen (O_2)) can have a negative impact on pipelines including fracture propagation, corrosion, non-metallic component deterioration and the formation of hydrates and clathrates. The most significant effect on transport and injection of CO_2 is the water content as hydrate formation can lead to the greatest interruption to flow (IEAGHG, 2016).

The impacts of impurities in the CO_2 stream on pipeline, wellbore and reservoir integrity has been extensively researched (Rütters et al., 2016) . This research has been utilized to produce CO_2 stream specifications capture sources must comply with. Refer to the CCUS Network's report "Briefing on Carbon Dioxide Specifications for Transport" for more information regarding CO_2 specifications, including current international standards.

The compositional requirements for the CO_2 stream are therefore established early in a project's development. The specification must be carefully balanced: stringent enough to prevent any negative side-effects to infrastructure but also not overly restrictive to prevent CO_2 sources joining the project. The development of a CO_2 specification means the CO_2 stream composition is guaranteed throughout a project's lifetime and requires limited flexibility during the project's operations. An example of a project's CO_2 specification requirements is included in Appendix A for the Northern Lights project.

This report on operational flexibility is more focused on how projects incorporate changes in flow rate into their operational plans as this is more likely to require active management during a project's operational lifetime.

2.3 Impact of Changes in CO_2 Stream Flow Rate

For most transport projects the development of a two-phase CO_2 stream is avoided[2]. The stream should be kept in a single phase during transportation, usually liquid or supercritical, which requires constant temperatures and pressure to be maintained (Witkowski et al., 2014). Phase changes should be avoided as they can cause the separation of gas components which may lead to corrosive effects. Changes in flow rate can make it more difficult to maintain the temperature and pressure of the CO_2 stream within the designed pipeline operating conditions (Jensen, Schlasner, Sorensen, & Hamling, 2014). Onshore, pressures are usually maintained using compressor stations but this is not an option offshore (IEAGHG, 2016).

Alongside corrosion, changes in the CO_2 stream flow rate and intermittent flow can impact pipeline and wellbore integrity through fatigue and hydrate formation. Flow rates must be maintained to allow wellbores and pipelines to meet temperature requirements. The temperatures required are dependent on the materials used. As an example, generally the temperature at the wellhead (after the topside choke) at most wells should be above -10°C to limit thermal stresses in the topside equipment. Operators must therefore ensure flow rates are kept as regular as possible to minimize these potential side effects.

2.4 Operational Experiences Handling CO_2 Stream Variability

There are now 19 CCS projects operational globally (Global CCS Institute, 2019), most of which have experience handling flexibility, albeit to different extents, within their projects. IEAGHG reviewed five CCS operations in 2016 to study operational flexibility (IEAGHG, 2016). The case studies were Sleipner and Snøhvit in Norway, Weyburn and Illinois-Decatur in North America and In Salah in Algeria.

The report concluded that all the projects experienced mass flow variability or interruptions in flow during their operational lifetime. Mitigation strategies were implemented at each of the sites which managed to accommodate the effects of intermittent flow. The report also revealed that most CO_2 pipelines in the USA were overdesigned for their current application. “They were designed for higher flow rates and operating pressures through the use of thicker walls and larger diameters. For example, the Denbury Greencore Pipeline began operation with a capacity of 0.96 Mtpa but was designed to carry up to 13.9 Mtpa. The additional pipeline dimension enables the company to expand its network’s carrying capacity” (IEAGHG, 2016) which allowed the project some flexibility on the amount of CO_2 they could transport. A key conclusion from the report is that:

> *“Networks can be a useful means to control flow in a pipeline and can also act as a buffer by supplying* CO_2 *from several sources to a number of different sinks. Multiple sources also mean that there is less reliance on a single source and intermittent supply from different sources can be accommodated.* CO_2 *can also be temporarily compressed or ‘packed’ into pipelines as a short term measure.”*

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[2] Refer to Section 2.1 for more details regarding CO_2 properties: http://publications.europa.eu/resource/cellar/4ab1c4e2-398e-426c-b06f-1175d3c5a403.0001.02/DOC_1

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Sleipner had a single capture source and storage location and had avoided any supply or logistical difficulties. Planned maintenance had taken place, which included 4-week workover periods once every two years. As these were planned well in advance, they were conducted without any negative impacts to infrastructure or reservoir geology. In comparison, the enhanced oil recovery (EOR) site in Weyburn, Canada, also experienced two planned interruptions in CO_2 supply but continued injection by utilising recycled CO_2 reproduced during operations alongside the extracted oil. Although during these periods oil production was reduced it recovered again after the maintenance periods, it was therefore assumed that no damage was caused to the infrastructure or reservoir during these periods.

Although interruptions in flow rate can cause inevitable changes in pressure within pipelines and wells, the EOR industry in the United States has proven it is possible to adapt variability and intermittency to avoid unintended multiphase flow and any corrosion of infrastructure (IEAGHG, 2016).

2.5 Developing a Flexible European CCS Network

An important building block to allow a large-scale CCS network to develop in Europe is the ability to continuously incorporate flexibility throughout the projects' lifetime. If projects are able to develop the ability to handle varying amounts of CO_2 within their operations this will be beneficial. This may allow, in the long-term, more CO_2 sources to be added to the transport and storage network as they come online. Many smaller projects currently ongoing rely on a single source and geological storage site (e.g. Sleipner) which means they are very reliant on a single source to provide a consistent CO_2 stream. Adding more sources to a single transport and storage network, although the stream composition and flow rate becomes more complex, provides the availability to allow different sources to come on and offline at different times (e.g. for planned maintenance).

This report presents two CCS project case studies to highlight how operational flexibility has been developed and how the design of the transport and storage network handles potential changes in CO_2 flow rate.

3 Northern Lights Project

This part of the report aims to summarise the Northern Lights project and highlight the approach being taken towards operational flexibility.

3.1 Project Introduction

The Northern Lights project is intended to be a commercial CO_2 transport connection project between several European capture initiatives. The project will also provide a storage site on the Norwegian Continental Shelf to provide storage to numerous CCS projects.

The Northern Lights project comprises the transport and storage aspect of the Norwegian Full-Scale CCS Project. The concept and FEED studies are currently being undertaken in a joint venture between Equinor, Shell and Total.

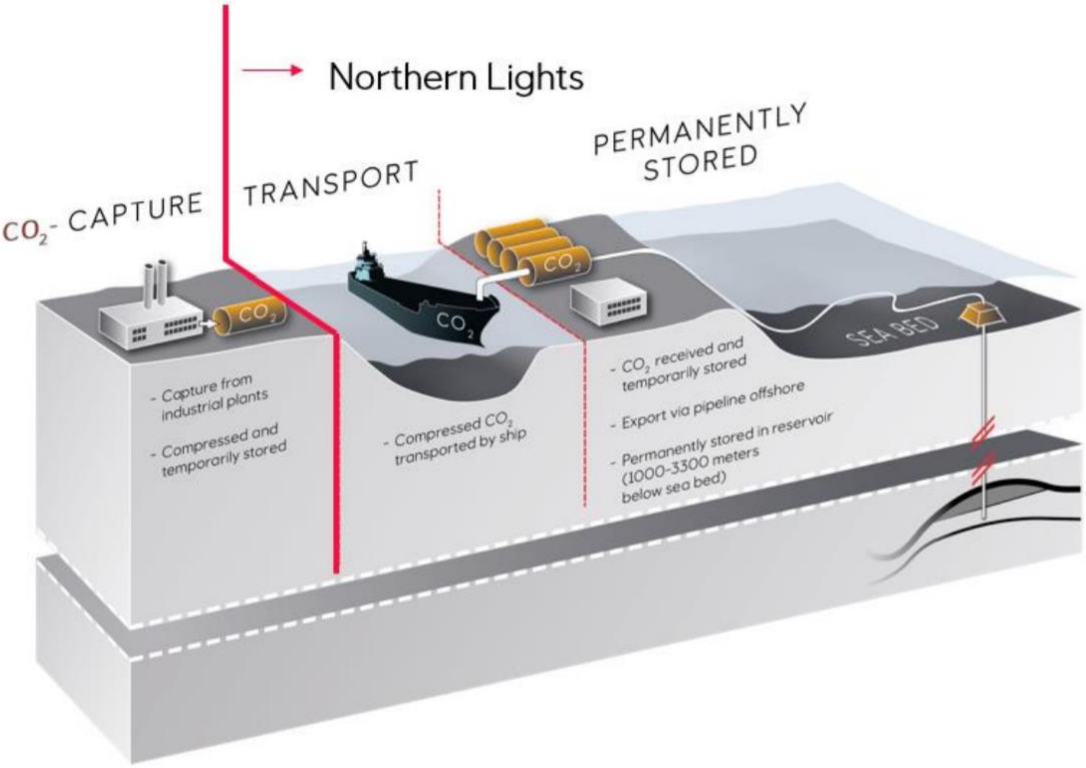

Figure 1: Schematic of the Northern Lights project, shown as part of the full-chain Norwegian CCS demonstration project (Source: Equinor, 2019).

The CO_2 will be collected by ship from industrial capture sites across Europe and then transported and offloaded to a temporary storage site, comprising of tanks, onshore in Western Norway. These tanks will act as temporary storage buffers before the CO_2 is then transported by pipeline to an offshore geological storage site, the Aurora field. Equinor was awarded an exploitation permit for CO_2 storage in Aurora on 11 January 2019 and drilling is currently being undertaken as part of the site characterization process. A summary of the project is presented in Table 1.

Table 1: Summary of Northern Lights project characteristics

Northern Lights	
CO_2 Source	The capture aspects are outside the scope of the Northern Lights project which takes responsibility for the CO_2 on delivery at the jetty. Numerous capture sources planned in the long-term. **Phase 1:** CO_2 captured as part of Norway's full-chain CCS plans: - Fortum's waste-to-energy plant at Klemetsrud - Norcem's Heidelberg Cement site in Brevik Both sites produce approx. 400 ktpa of CO_2 and will have CO_2 captured and stored locally at their jetties. Storage volume at each site is required to account for ship arrival every four days plus a buffer for any upsets in the overall chain. Jetty operations are the responsibility of the capture plant. Phase 1 for Northern Lights has a total capacity of 1.5 Mtpa of CO_2, which allows for spare capacity in addition to the two Norwegian capture sites. This spare capacity is intended to be filled with industrial CO_2 from European sources. **Phase 2:** Phase 2 will expand the capacity up to a total of approximately 5 Mtpa. Phase 2 will aim to continue to incorporate CO_2 capture sites across Europe. Seven European companies have signed MoUs so far (Air Liquide, Arcelor Mittal, Ervia, Fortum, Preem, HeidelbergCement, and Stockholm Exergi).
Transport Network	CO_2 is transferred from capture facilities in ship cargo tanks at a pressure of 15 bar(g), with corresponding equilibrium temperatures. One ship will be utilised per capture site, 7500m^3 CO_2 capacity per ship. CO_2 will be transported as a single-phase liquid. CO_2 is transferred from ship cargo tanks to temporary onshore storage tanks at the Northern Lights terminal at a pressure between 13 and 18 bar(g) at the top of the onshore storage tanks, with corresponding equilibrium temperatures. Appendix A outlines the CO_2 specification. A 100 km 12" pipeline will transport CO_2 from onshore temporary storage to offshore permanent storage site. The pipeline is designed to allow for a future flow rate in Phase 2 of approximately 5Mtpa. A flow assurance strategy will be adopted to ensure single-phase liquid flow of CO_2 throughout transportation.
Geological Storage (Aasen, 2020)	Storage will be in the Aurora field (Lower Jurassic Johansen Formation, south of producing Troll Field) at approximately 3000m depth. Pressure in reservoir is hydrostatic at approx. 250-300 bar. Temperature in reservoir is approx. 100 °C. Minimum expected capacity of 100 Mt of CO_2. The design assumption has been that each well will have a capacity of around 1.5 Mtpa of CO_2 injection.

3.2 Conceptual Approach

The Northern Lights project is different from many previous CCS demonstration projects as the source of CO_2 and the transport and storage network are decoupled. As a concept this allows for more flexibility which is key for further market development in the future.

Northern Lights will be an “open access” service for the transport and storage of European CO_2, with the capture plants responsible for getting CO_2 to a terminal ready for ship transportation. CO_2 from numerous capture sources is therefore expected to be transported to the same offshore storage site in Norway.

The current project design is based on 2 phases. Phase 1 is designed with enough flexibility to include the additional volumes planned for Phase 2. The increase in capacity moving from Phase 1 to 2 is subject to incremental investments for increased capacity: (See Figure 2)

> *Phase 1:* Capacity to transport, inject and store up to 1.5 Mtpa of CO_2. Phase 1 is planned to be operational in 2023, given a positive FID from the Northern Lights partners in Q2 of 2020 and the Norwegian State by end of 2020.
>
> *Phase 2*: Dependent on future support from the partners and suitable market conditions Phase 2 could then be developed. Assuming that the CO_2 transport capacity in Phase 1 is filled, Phase 2 would increase the capacity to receive, inject and store up to approximately 5 Mtpa of CO_2.

The total capacity for Phases 1 and 2 is therefore 5 Mtpa but the Northern Lights project is also expected to have significant spare storage capacity for volumes beyond these initial phases.

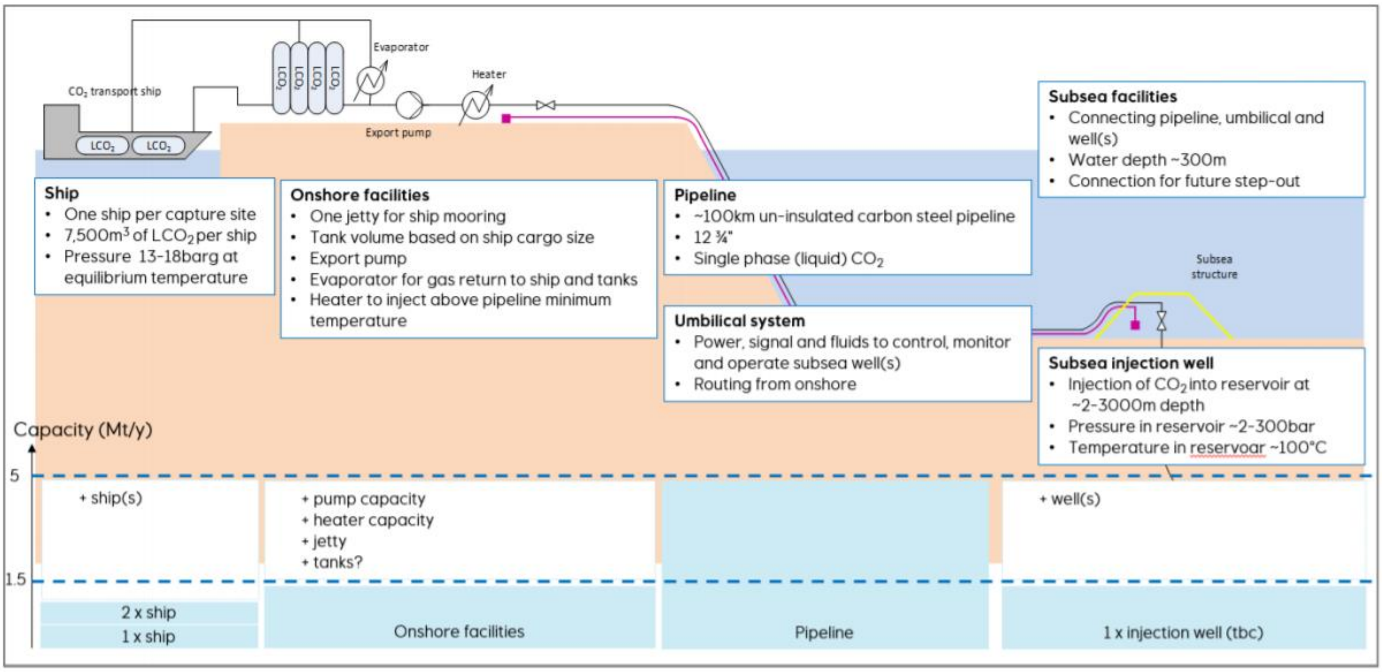

Figure 2: Northern Lights concept building blocks with capacities in the first phase shown with blue shading (Source: Equinor, 2019).

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3.3 Operational Flexibility

3.3.1 How is flexibility incorporated into the operational design?

Norway's long-term ambition is to develop a full-CCS chain to transport CO_2 from across the European continent. The project has therefore been designed with future expansion in mind. The decoupling of source and sink and a cluster rather than point to point system is the key concept allowing flexibility within the separate transport and storage network developed.

The Northern Lights infrastructure including ships, the receiving terminal, offshore pipeline, and the umbilical system to the subsea facilities have all been designed to receive additional volumes beyond the 800 Ktpa from the initial Norwegian capture projects Fortum and Norcem. The number of intermediate onshore storage tanks can be increased if required, and there is also an option for building a second jetty to be able to receive two tankers at a time. The pipeline from the receiving terminal can transport the volumes of CO_2 required and additional wells can be connected to the end of the pipeline. ("Transport and storage: Northern Lights," 2020)

Both Phase 1 and 2 will offer flexibility to receive additional volumes from European CO_2 sources, up to 1.5 Mtpa and 5 Mtpa respectively, for the two Phases. Numerous capture initiatives across Europe could use Northern Lights as their primary transport and storage solution. The total potential volumes of CO_2 from these additional capture sites add up to approximately 300 Mtpa from 350 potential sources of CO_2. Further expansion phases could therefore be considered by project partners subject to market conditions and a final investment decision. (European Comission, 2019)

The requirement to have single-phase liquid CO_2 throughout transportation requires careful operational management of the system. The current ship design is optimized for the volumes and distances in the Norwegian full scale project and as such has a specified design and hence capacity, however, Northern Lights will revisit the ship design if/when needed. Pipelines have to maintain certain pressures to prevent two-phase flow. Incorporating interim storage into the transport and storage system is therefore valuable as it allows pressure to be maintained at various stages along the chain. During phase 1 the onshore tanks can hold the same amount of CO_2 as one ship, and one ship delivery is planned every four days. This incorporates some margin for change in shipment delivery but areas are planned for more onshore storage tanks to be developed in the long-term. The site for the onshore facilities, Naturgassparken in Øygarden, was selected for its development potential. The pumps required for pipeline transportation will also have a large operational capacity window, to allow for changes in CO_2 volume.

3.3.2 Are additional costs associated with this flexibility?

The staged development of Northern Lights allows for numerous investment decisions to be made as the market develops. For Phase 1, the FID for the project partners Equinor, Shell and Total is scheduled for Q2 2020, and the Norwegian State FID is set to be made in 2020/2021.

Phase 1 is developed with flexibility for further capacity expansion through additional building blocks. This is valid for ship transportation, which gives more flexibility in terms of sizing and source location compared to a pipeline. The onshore tank capacity is dimensioned based on ship cargo volume and not throughput. A higher throughput can therefore be realized by adding ship frequency to bring CO_2 to the plant, and adding wells for higher injection capacity into the storage. Pre-investments have been kept to a minimum for capacities above 1.5 Mtpa, with the exception of the pipeline from the onshore terminal to the injection well. Based on a cost-benefit analysis the pipeline has been dimensioned for phase 2 in the initial development to avoid laying a new pipeline for this phase.

3.3.3 What are the responsibilities of the CO_2 supplier?

Northern Lights will provide the transport and storage network, while the capture plant will have the responsibility to capture, liquify, store intermittently and transport the CO_2 to the loading terminal for ship transportation. Northern Lights have ensured that these operations are the responsibility of the emitters and not included in the project scope. This is because these aspects involve an intimate knowledge and interface with ongoing industrial operations at the capture plants which the operator has the best insight into. Typically Northern Lights will take responsibility from the battery limit between the loading terminal and the ship, however in certain cases this interface can take place at a different point in the value chain. E.g. some emitters might prefer to do their own ship transportation all the way to the Northern Lights CCS onshore facilities on the west coast of Norway.

The Northern Lights chain enables simplicity and ability to tailor arrangements to meet each third party supplier of CO_2 and their specific needs.

The commercial arrangements between Northern Lights and the CO_2 emitters will need to cater for specific requirements relevant for the emitters and Northern Lights. One way the contracts could be structured would be ‘take-or-pay’ (or rather ‘supply-or-pay’), whereby the emitter has a right to supply and/or deliver volume and rates, over a defined time period (e.g. 20 years), against a tariff. Such an option would build on the way gas offtake agreements have historically been structured.

4 Porthos Project

This part of the report aims to summarise the Porthos Project and highlight the approach being taken towards operational flexibility.

4.1 Project Introduction

Porthos is a CO_2 transport and storage project being developed in the Port of Rotterdam in the Netherlands. Porthos is a collaboration between the Port of Rotterdam Authority, Gasunie and EBN and encompasses the transport and storage elements of a full-chain project.

The Rotterdam Port Area is a major emitter of CO_2. Due to the large-scale heavy industry in the Port of Rotterdam, there is large potential for climate change mitigation through CO_2 capture and storage. The area comprises 5 large oil refineries, production plants for hydrogen, industrial gas producers, and a variety of chemical (45 chemical locations) and power generation (9 plants) sites which include both coal-based and gas-based sources. The estimated CO_2 emission levels in the Port of Rotterdam region (from the port plus industries in the area) during 2018 were are around 27 Mt ("Port of Rotterdam," 2020).

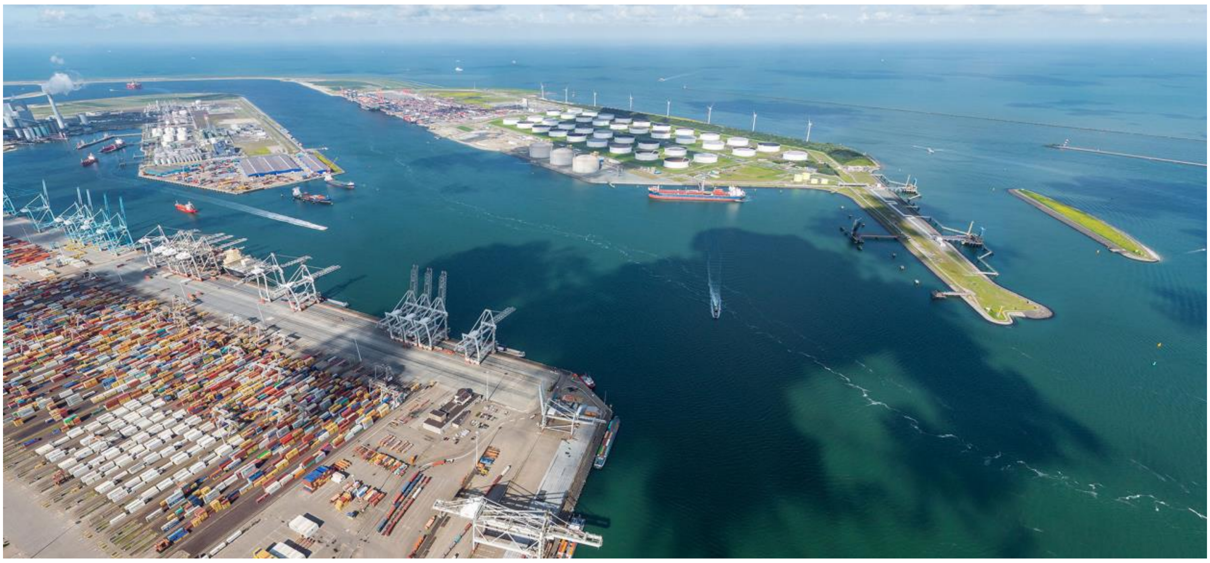

Figure 3 Maasvlakte area in the Port of Rotterdam where the compressor station will be situated and the onshore CO_2 pipeline will then be located offshore.

The capture of CO_2 is separate from the transport and storage responsibilities of the Porthos Project and will be from industrial sources in the area. The captured CO_2 will be delivered (at an appropriate composition and pressure) to a collection pipeline running through the port. Porthos will then transport the CO_2 via onshore pipeline to the compressor station at Maasvlakte and then via an offshore pipeline to a North Sea platform, 20 km off the coast of Rotterdam. A summary of the project is presented in Table 2.

Table 2: Summary of Porthos project characteristics

Porthos Project	
CO_2 Source	The capture aspects are outside the scope of the Porthos project. CO_2 suppliers are not yet formalised. Porthos intends to connect to CO_2 suppliers in the Port of Rotterdam. Potential customers are Air Liquide, Air Products, ExxonMobil and Shell. The Porthos infrastructure will also be suitable for transporting CO_2 for use by industry, if there is demand for this in the future.
Transport Network	Porthos will provide a communal pipeline for industry to connect to but the supply pipeline from the capture location to the central transport pipeline is not considered part of the Porthos infrastructure. The onshore pipeline has a diameter of 108 cm and a length of approximately 30-33 kms. The pipeline's operating pressure will be between 15 and 40 bar. CO_2 will be in a gaseous phase and the pipeline will have a capacity of 5 Mtpa CO_2. A compressor station is required. There are three possible locations for the compressor station: either Edisonbaai, Europaweg and Aziëweg located on the Maasvlakte. CO_2 will be supplied at a pressure up to 40 bar and approximately 15°C, in the gas phase. The compressor will then increase the CO_2 pressure to approximately 85-120 bar and the temperature to 30-80°C. CO_2 will be transported offshore in gaseous phase with the properties of a liquid. The offshore pipeline to the platform has a length of approximately 22 km and a diameter of 40 cm. The route of the transport pipeline on the seabed to platform P18-A partly follows an already existing gas pipeline at a safe distance and thus follows approximately the same route as used in the preparation of ROAD[3]. The CO_2 pipeline will be connected to platform P18-A using a vertical riser.
Geological Storage	Three storage sites are planned: the P18-2, P18-4 and P18-6 depleted gas fields in the North Sea, all accessible from the P18-A platform. TAQA is the operator and EBN is a co-shareholder in the natural gas extraction. TAQA already has a CO_2 storage permit for P18-4. The storage capacity of the reservoirs P18-2, P18-4 and P18-6 together is approximately 37 Mt CO_2. Dependant on the annual quantity, this can average 2-3 Mtpa of CO_2 for approximately 15 years. The depth of the gas fields is between 3.18 and 3.46 km.

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[3] For more details regarding the ROAD project refer to: https://setis.ec.europa.eu/publications/setis-magazine/carbon-capture-utilisation-and-storage/road-%E2%80%93-rotterdam-capture-and

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4.2 Conceptual Approach

The Porthos project's approach to flexibility is more linear than that of Northern Lights with capture only planned in one industrial area and no intermittent storage. Numerous capture sites will be incorporated which allows for some flexibility in supply should certain capture sources not be able to provide the planned CO_2 quantities. The project is described as developing in the following stages (Royal Haskoning DHV, 2019), which are also shown schematically in Figure 4:

1. Construction and use of the onshore CO_2 transport pipeline starting from Petroleumweg (east of the Oude Maas).
2. Construction and use of the location and layout of the compressor station on the Maasvlakte.
3. Construction and use of the CO_2 transport line from the location of the compressor station to the platform P18-A (offshore):
    - From the compressor station to the low-water line (onshore);
    - Crossing of the Maasgeul (offshore);
    - North Sea ocean floor up to the P18-A platform (offshore).
4. Adjustment and use of platform P18-A for CO_2 injection, including adjustment of injection wells.
5. Use of reservoirs P18-2, P18-4 and P18-6 for CO_2 storage.
6. Infrastructure management and operation.

The project operations are designed so that CO_2 suppliers (capture plants) add CO_2 to the transport pipeline. The CO_2 will have to comply with stipulated, pre-agreed gas quality requirements (composition, pressure and temperature). At the compressor station the flow rate and the gas quality will be determined before transport to the offshore platform takes place.

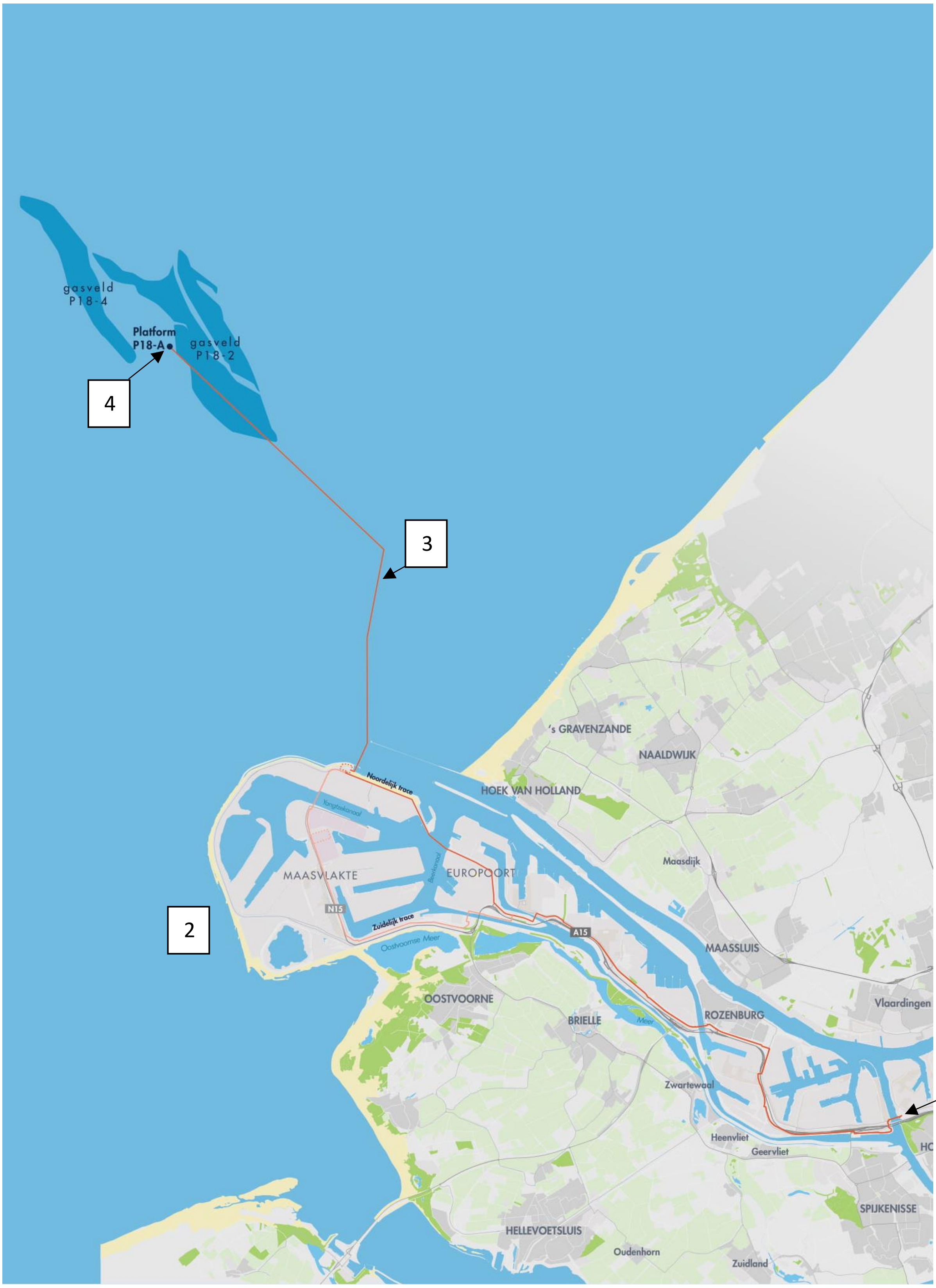

Figure 4: Overview of infrastructure and reservoirs for Porthos Project (Source: Royal Haskoning DHV, 2019). The storage reservoirs are shown in dark blue. The red lines indicate the north and south CO_2 pipelines. Numbers indicate the text reference from Section 4.2, the exact location of the compressor station (2) is not yet confirmed.

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4.3 Operational Flexibility

4.3.1 How is flexibility incorporated into the operational design?

To increase the future capacity of the project, the Porthos project’s infrastructure has been designed with potential expansion options taken into consideration, such as:

- Expansion of the infrastructure through:
    - Additional connection points on the transport pipeline for pipelines from CO_2 suppliers;
    - Expansion of the transport pipeline for new CO_2 suppliers;
    - Expansion of the transport pipeline at sea to new storage locations.
- Later expansion of the underground storage locations by preparing the platforms and wells for CO_2 injection and storage.
- Connection of the pipeline to users of CO_2 (utilization).

This makes Porthos suitable in the current set-up for possible future developments.

4.3.2 Additional costs and supplier contracts

The Porthos Consortium is currently engaged in negotiations with the Dutch government regarding the implementation of costs in the national subsidy-scheme, so no information is currently publicly available regarding the costs associated with this project.

No information is yet available on supplier contracts which are also yet to be established but likely to be signed in 2020.

5 Role of Future Research

A majority of research to date has focused on the technical aspects regarding the impacts of varying CO_2 streams, e.g. on pipeline integrity or decreased injectivity into the storage reservoir. It is therefore important to establish the role future pilot projects can play in furthering this knowledge and allow future projects to effectively incorporate operational flexibility into their management plans.

Pilot projects still have an important role to play in this aspect of R&D to study the potential long-term impacts of varying flow rate and composition on pipeline, wellbore and reservoir integrity. Further knowledge will help large-scale projects establish the safe limits within which pipelines and wells can be operated.

Business aspects, such as supplier contracts and the costs associated with added flexibility, will become more apparent as the next generation of commercial large-scale projects (such as Northern Lights and Porthos) begin to make more information publicly available. Suitable CO_2 specifications have already been developed, e.g. Appendix A for Northern Lights, but will be highly project specific dependant on the capture sources, pipeline and wellbore materials, and the geochemistry of the storage site. There is still more knowledge required on the associated costs of incorporating flexibility. For example, a comparison between the costs associated with capture plants meeting high purity requirements versus the costs associated with the operation of pipelines and wells when handling less pure $CO_{2.}$

Establishing and maintaining suitable flow rates is a complex issue. Future research and pilot projects could develop knowledge on suitable temperature and pressure constraints to prevent multiphase flow, for example within the restrictions of already existing oil and gas infrastructure. More experience is required in order to understand the nature of the CO_2 flow, the range of slug speeds, and induced stresses on the pipeline during transportation.

6 Conclusions

This report provides an overview of operational flexibility and its importance for future large-scale CCUS projects in Europe. As projects are developing from demonstration scale, single CO_2 source projects to larger commercial scale projects incorporating numerous capture sites, operational flexibility will become more complex.

The case studies presented here, Northern Lights and Porthos, have separated the transport and storage network from the full-chain project as a separate development. The composition will be defined in the specifications which will be the responsibility of the capture plants to meet. Flow rate will have to be carefully managed as numerous CO_2 sources come on and offline and the volumes of CO_2 entering the transport and storage network may vary.

Previous projects, for example EOR operations in North America, have already demonstrated that changes in CO_2 flow rate can be safely and effectively managed to prevent any detrimental impact on the pipelines, wellbores or the storage reservoir.

6.1 Next steps

This report will be provided to the Commission and the EU CCUS Projects Network intends to discuss the key viewpoints and remaining questions during the forthcoming knowledge sharing event. The responses from the Commission will then be shared with Network members where appropriate. Unresolved issues will remain on the agenda of the Thematic Group on CO_2 Transport, Storage, and Networks and the Network Secretariat will take efforts to address them.

7 Glossary of abbreviations and units

CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture utilisation and storage
CO_2	carbon dioxide
EOR	enhanced oil recovery
EU	European Union
FEED	front-end engineering design
FID	final investment decision
GHG	greenhouse gas
km	kilometres
kt	kilo-ton
ktpa	kilo-tonnes per annum
m^3	cubic meters
MoU	memorandum of understanding
Mt	mega-ton
Mtpa	mega-tonnes per annum
ppm	part per million

8 References

Note: Links are provided to websites and "grey" literature, where available. These have been checked at the time of referral or final editing, but their ongoing validity cannot be guaranteed.

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Appendix A

Component	Concentration, ppm (mol)
Water, H_2O	≤ 30
Oxygen, O_2	≤ 10
Sulphur oxides, SOx	≤ 10
Nitric oxide/Nitrogen dioxide, NOx	≤ 10
Hydrogen sulfide, H_2S	≤ 9
Carbon monoxide, CO	≤ 100
Amine	≤ 10
Ammonia, NH_3	≤ 10
Hydrogen, H_2	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury, Hg	≤ 0.03
Cadmium, Cd Thallium, Tl	≤ 0.03 (sum)

Table 3 CO_2 Specification for the Northern Lights project (Equinor, 2019)