DEVELOPING LONGSHIP

KEY LESSONS LEARNED

Experiences from the Norwegian
Full-scale CCS Demonstration project

GASSNOVA

CONTENTS

Gassnova SF
Developing Longship – key lessons learned

Rev. 01–2020

Layout and print: ETN Grafisk / Erik Tanche Nilssen AS

PREFACE

Norway has a long history of carbon capture and storage (CCS). Gassnova has been working with all stages of the development of CCS since 2005, from R&D to industrial scale. The main goal of our work is to contribute to technology development and cost reductions and enable deployment of CCS through knowledge sharing and experience transfer together with our partners. The Norwegian Full-scale CCS project, named Longship, is a result of exactly this objective.

Through a unique long-term cooperation between the Norwegian state and government agencies, R&D institutions, academia and the industrial partners in the project we have jointly managed to mature and develop CCS technology and a full-scale project that is now ready for industrial deployment. In particular I want to acknowledge Norcem Brevik, Fortum Oslo Varme and the Northern Lights partnership who has put a lot of efforts and resources in sharing their learnings and experience from the development of the projects in a very professional and cooperative manner.

Gassnova's report on the key lessons learned from the planning of Longship is based on the knowledge shared by the industrial companies involved, our own experience from following up and coordinating the project and also our long history of working with the development of CCS technology.

My hope is that the information shared will be useful for ongoing and coming CCS projects, authorities in other countries, and for companies and organizations with an interest in CCS. With continued joint efforts we can further develop the CCS technology and reduce the cost.

Trude Sundset

Trude Sundset, CEO Gassnova SF

LONGSHIP AT A GLANCE

Longship covers the capture of CO_2 from Norcem HeidelbergCement's cement factory in Brevik and from Fortum Oslo Varme's waste-to-energy plant in Oslo. The captured CO_2 will be shipped in liquid form to a CO_2 receiving terminal on the Norwegian west coast. From there, the liquefied CO_2 will be transported by pipeline to an offshore storage location under the North Sea for permanent storage. The transport and storage part of the project is a collaboration between Equinor, Shell and Total called the "Northern Lights Project".

On 21st September 2020 the Government proposed to realize the Longship project with the three industrial partners Norcem, Fortum Oslo Varme and Northern Lights. The state aid to Fortum Oslo Varme will be given provided that they secure sufficient own funding as well as funding from the EU or other sources. Realization of Longship is subject to approval by the Parliament in December 2020.

> This is a first-of-its-kind project when it comes to: the emission sources where the CO_2 will be captured; the scalable transport and storage infrastructure ready to be used by other emission sources; and the application of European and Norwegian CCS regulations. The different technical solutions are in operation elsewhere but are put together for the first time to form a complete CCS chain.

Although Norcem, Fortum Oslo Varme, and the Northern Lights partnership have received state aid throughout the project development, each industrial partner is responsible for their own project.

Gassnova is a state enterprise owned by the Ministry of Petroleum and Energy (MPE) and has been administering the public funds to the industrial partners through agreements for study of capture, transport and storage of CO_2. It has also coordinated the overall project schedule and managed the cross-chain risks and functionality. MPE has been leading the negotiation with each industrial partner on the terms for the state aid for the potential construction and operation of the CCS-facilities.

In a Government White Paper to the Norwegian parliament submitted on 21st September 2020, the Government proposed to launch a carbon capture and storage (CCS) project in Norway. Named 'Longship', the project has been developed over the past 6 years and the Final Investment Decision will be taken by the Norwegian Parliament in December 2020.

EXECUTIVE SUMMARY

This document sums up what Gassnova considers to be the key learning points from the project up to this point. Although the project has been developed under circumstances that are unique for Norway, the experiences are relevant for the setup and development of other CCS projects. At a glance, these are:

- Developing a CCS chain with CO_2 capture, transport by ship and geological storage is technically feasible and safe, but commercially challenging.

- The London Protocol that has been a barrier for cross-border transport and storage of CO_2. However, in 2019 the parties to the London Protocol agreed on a temporary amendment allowing export of CO_2 for the purpose of storage offshore. Aside from this, no regulatory showstoppers have been identified so far.

- It has been possible to develop the CCS chain with limited use of new technology, and only for the amine technologies used to capture of CO_2 there are no fallback solutions.

- Although there are few comparable CCS chains world-wide, experienced and competent contractors and suppliers can be mobilized and the technical know-how is readily available.

- As expected for a first-of-its-kind CCS project, the net cost per tonne for capture, transport and storage is high; for 800,000 tonnes per year the cost is around NOK 1,280, which will decrease with full utilization of the transport and storage facilities.

- The time needed to perform detailed engineering and construct transport and storage facilities based on ships and a greenfield CO_2 receiving terminal is approximately 36 months. For a capture plant retrofitted onto an existing industrial plant, this will take up to 42 months.

- Upon approval by the Parliament, Norcem and Northern Lights will each enter an agreement with the government providing state aid to the construction and first ten years of operation of the CCS-facilities. Reflecting the balance between risks and opportunities in these agreements, the state will bear approximately 84% and 73% of the expected cost of Norcem's and Northern Lights' projects, respectively. The government is ready to cover 40% of Fortum Oslo Varme's cost provided that they are able to secure additional funding from third parties.

ABOUT THIS DOCUMENT

This document presents key learnings from the development of Longship from the pre-feasibility study in 2014 up to completed FEED studies and the industrial partners FID's in 2020. Maximizing the value and availability of "lessons learned" from the Norwegian CCS efforts is part of Gassnova's mission. The key learnings have been formulated as seen through the eyes of Gassnova as a public "project integrator", and when the learnings are characterized as "successful", they must be understood in this perspective: the project has matured to the right level, the industrial partners have taken their investment decisions, and the government is ready to take the FID.

The learnings presented here are primarily related to CCS-specific aspects of the project, indirectly touching upon the public financing. General project experiences are mostly omitted. The aim of this document is not to make firm recommendations, but rather to present central lessons learned to assist anyone who has an interest in developing CCS.

This document is structured around the framework of the project (Chapter 01), as well as the project development itself (Chapter 02). However, it also draws on Gassnova's wider experience in the development of CO_2 capture technology (Chapter 03).

The different parts of the project are presented in more detail in the FEED study reports from Gassnova and the industrial partners, namely Fortum Oslo Varme, Norcem, and Northern Lights*.

* These reports, and others, are available at ccsnorway.com/

Glossary

Availability Fraction of time when a system is operational, assuming that the required external resources are provided. External resources are e.g. production of cement or incineration of waste, and supply of electricity from the grid.

AACE American Association of Cost Engineers

CCS Carbon capture and storage

ESA EFTA Surveillance Authority

EU ETS EU Emissions Trading System

FEED Front End Engineering and Design

FID Final Investment Decision

IEA International Energy Agency

IMO International Maritime Organization

KS2 External quality assurance of project control basis and cost estimates before FID

LPG Liquefied Petroleum Gas

LNG Liquefied Natural Gas

MPE Ministry of Petroleum and Energy

NPD Norwegian Petroleum Directorate

R&D&D Research, Development and Demonstration

SMART Specific, Measurable, Achievable, Relevant and Time-bound

TCM Technology Center Mongstad

INTRODUCTION

Previous CCS experiences in Norway

The Norwegian Continental Shelf has a vast capacity to store CO_2 in geological formations, and a stable and broad political will to fund CCS R&D has resulted in Norwegian research entities and companies working in the field of CCS for a long time. When the "Sleipner" CCS Project was commissioned in 1996 it was the world's first offshore CCS plant. More than a million tonnes of CO_2 have been stored in the Utsira formation below Sleipner every year since then. In the "Snøhvit" CCS project, CO_2 has been separated from raw natural gas at the onshore LNG plant at Melkøya and transported and stored offshore since 2008. Technology Center Mongstad (TCM) is the world's largest testing facility for CO_2 capture technology and was opened in 2012. These CCS operations and the surrounding R&D activities have helped to build trust in the technology among the Norwegian population.

Various Norwegian governments have long had an ambition to realize a full-scale CCS project. There have been attempts to develop CCS at the gas processing plant at Kårstø and the refinery at Mongstad while the current project is based on capture of CO_2 emissions from industrial sources. In developing Longship, the emphasis has been on using the expertise built up over many years through previous CCS projects, TCM and the R&D&D programme CLIMIT.

Background to the current project

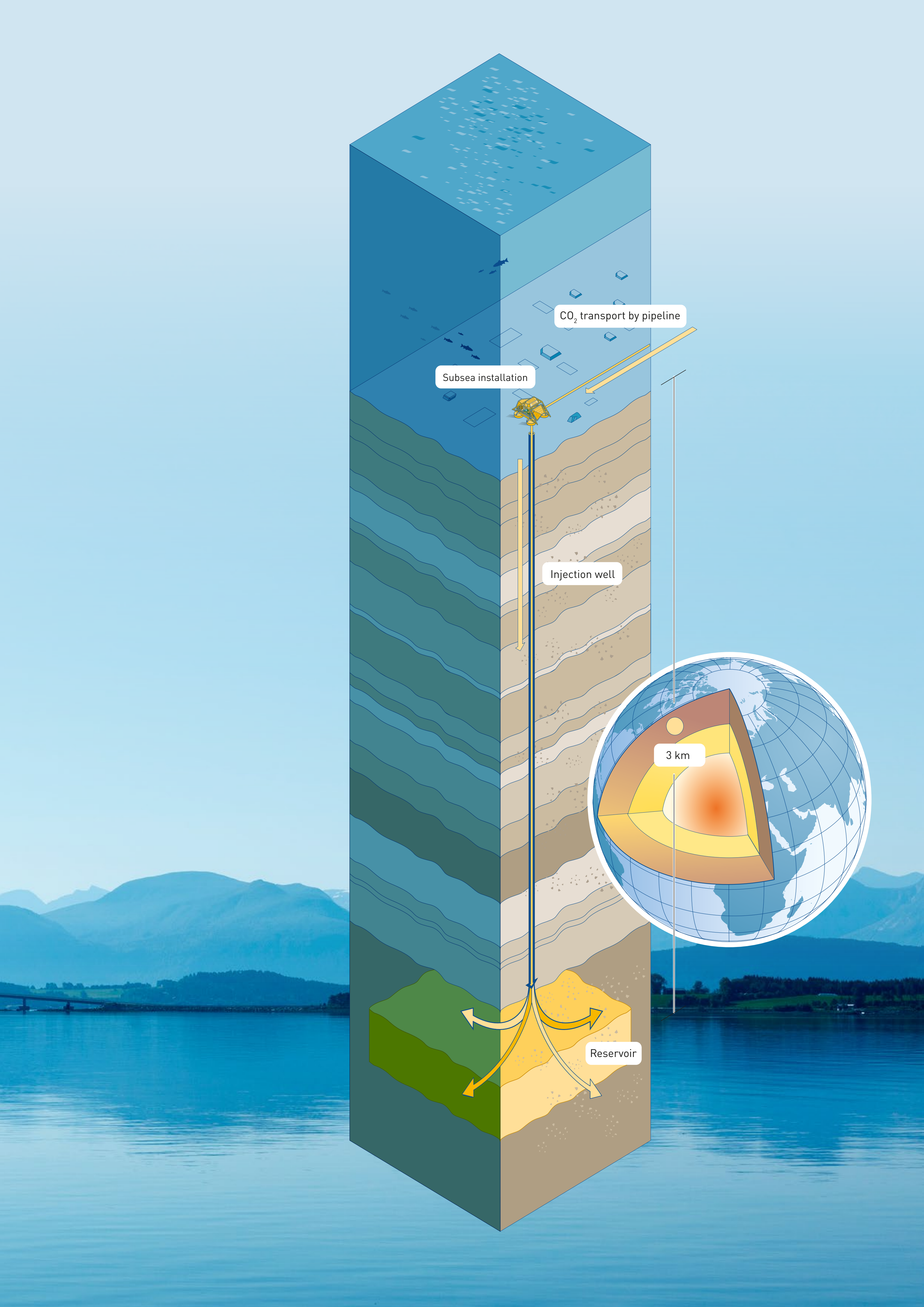
The Norwegian Government's CCS strategy was presented to the Parliament in Prop. 1 S (2014-2015). This strategy sums up the state's broad involvement in CCS activities in Norway and internationally which can contribute to technology development and cost reductions for CCS and describes an ambition to realize a full-scale project.

Although the need for CCS to meet long-term global climate goals has been well documented, IEA and others have for years constantly reported a portfolio of industrial CCS projects far below the identified need, even though technologies exist. Several barriers to commercial CCS investments have been identified. In order to overcome these investment barriers, there is a need for innovation related to business models, policy and regulations.

> Industry will not invest in technology with an uncertain future market potential, and policymakers cannot commit to a technology they do not know and whose future industrial interest is unclear. To break this deadlock, an industrial full-scale and full-chain demonstration is needed.

The way the Norwegian project has dealt with this situation is through a public-private cooperation based on trust and stepwise maturation of the project.

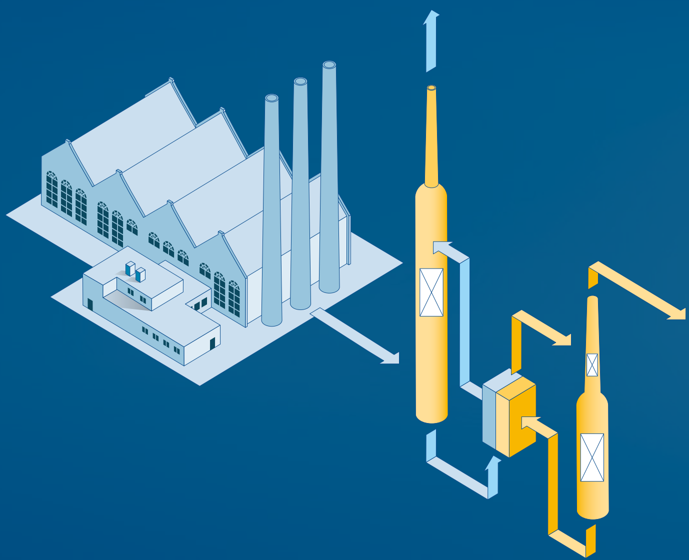
Based on the Government's CCS strategy, Longship has from 2015 been developed in stages with several industrial partners and according to best practices for industrial projects. Early on Gassnova recommended establishing a transport and storage operator that could offer transport and storage services to industrial parties who often do not have the required expertise and resources. The target segment for potential CO_2 capture sites is existing land-based emission sources with emissions above 400,000 tonnes of CO_2 per year. An important premise for the state is the self-interest the industrial partners have in CCS.



CO_2 transport by pipeline
Subsea installation
Injection well
3 km
Reservoir

01 FRAMEWORK

Based on feedback from the industrial partners in the early in the process, the CCS chain was split into the three individual areas of capture, transport and storage. Longship was therefore organized as several individual sub-projects, led and executed by the industrial partners themselves, but within a framework coordinated and integrated by Gassnova. The different parties have only been responsible for activities within their areas of competence and business, while the state carries the full-chain risk. This has been a key factor for successful development of an integrated CCS chain.



Project goals

The long-term objective of the project is to contribute to the necessary development of CCS, in order to meet long-term climate goals in Norway and the EU in a cost-effective manner.

Project goals defined by the government:

1. Demonstrate that full-scale CCS is feasible and safe.
2. Reduce the cost of future CCS projects through learning curve effects and economies of scale.
3. Generate learnings related to regulating and incentivizing CCS activities.
4. Contribute to new industrial opportunities.

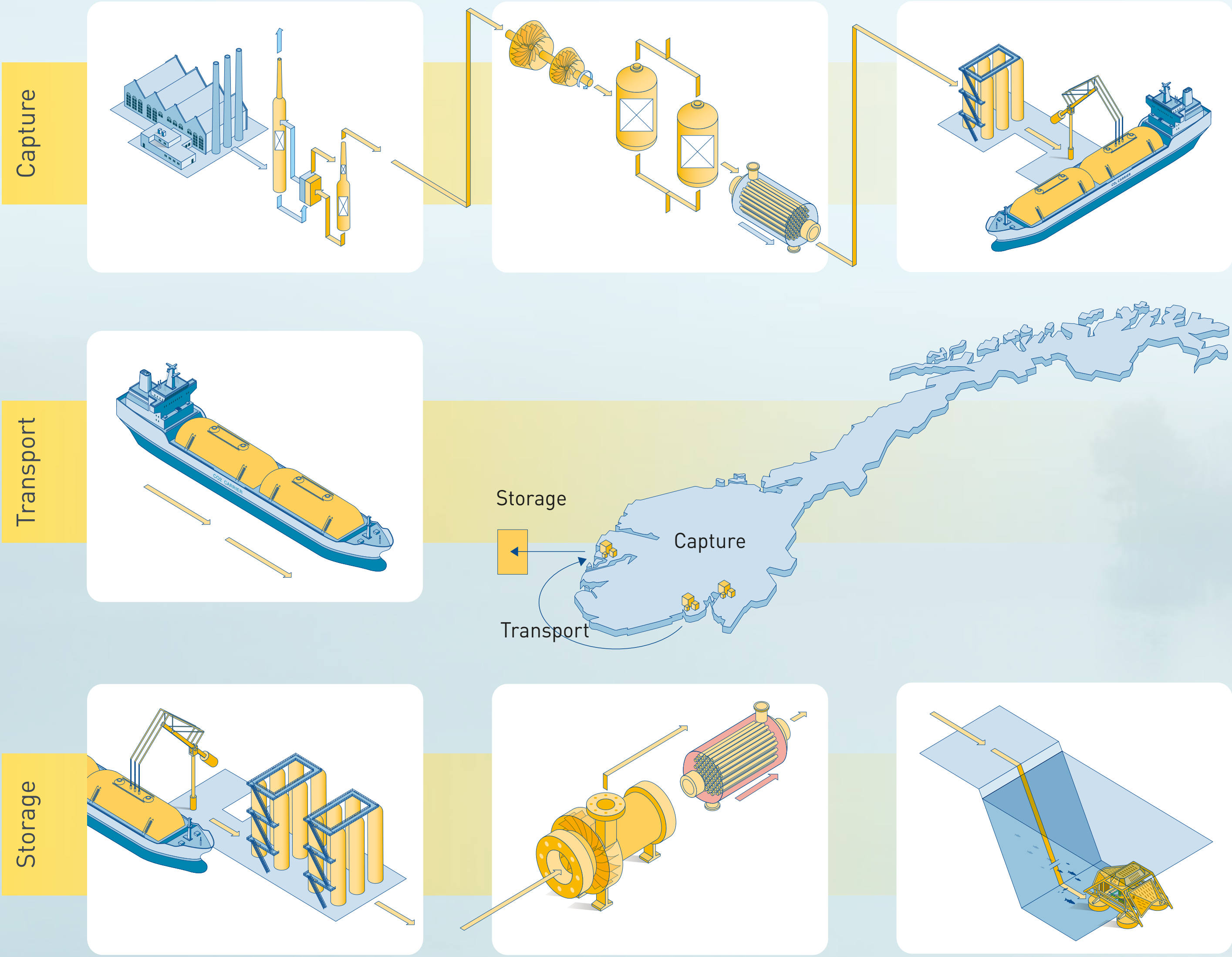
The Revised National Budget for 2018 underlined the importance of bringing the cost down and increased the likelihood of the Norwegian CCS chain becoming relevant for other European capture sources.

> In order to strengthen the industrial approach of the project, it has been left to each industrial partner to define and develop their project according to their best interpretation of the project goals.

In major decisions made by Gassnova, the emphasis has been on the first project goal, as any other goal is dependent on a successful demonstration. An example of such a decision is to transport the liquid CO_2 at the same pressure and temperature as used commercially today. While it is theoretically possible to achieve more cost-efficient transport at lower pressure/temperature, it would raise the complexity and risks in the project development.

Key learning points

- As the project goals describe the *desired effect* rather than specific and measurable targets, this has led to different interpretation of the project goals among the partners. On the one hand, this has allowed the partners to develop their projects to fit better with their business rationale. On the other hand, this has led to challenging discussions between Gassnova and the industrial partners regarding design performance.
- Defining clear project goals using e.g. the SMART principle and ensuring alignment between all project stakeholders should be given a high priority in early phases. This is particularly relevant for projects with a complex stakeholder environment, as is typically the case with CCS projects.


Capture
Transport
Storage
Storage
Capture
Transport

Project structure and the project integrator role

Based on feedback from the industrial partners in the pre-feasibility phase, the CCS chain was split into the three individual areas of capture, transport and storage. The main purpose of this division was to allow the emission source owners to focus on the capture element alone, without being burdened with the development of transport and storage solutions.

> Longship has therefore been organized as several individual sub-projects, led and executed by the industrial partners themselves, but within a framework coordinated and integrated by Gassnova.

This setup has left the risks associated with the development of the interface between the sub-projects to the state.

The work performed by the partners has been executed in line with study agreements with Gassnova, with significant state aid. Although the realization of the CCS chain will be largely publicly funded, the Norwegian state will not have ownership of any facilities or infrastructure. In order to allow the project to be developed on industrial terms, the degree of freedom given to the partners is significant, and the various sub-projects have been developed as the respective partners have seen fit.

A technical committee with participants from Fortum Oslo Varme, Norcem, Yara, Northern Lights and Gassnova has met on a regular basis (from the start of the concept selection phase) to discuss topics of common interest (e.g. related to CO_2 specification, export rates from the capture plants, use of loading arms between capture export terminal and ship, etc). Similarly, a committee for cross-chain operational aspects (e.g. principles for developing the ship transport schedule, how to handle off-spec CO_2 during loading of the ship, etc.) was actively working during the last stages of the definition phase.

As a consequence of the project setup, a project integrator has been needed. This role has included responsibilities such as:

- Definition of, and follow-up on, the studies through the whole project, incl. development of the design basis for the CCS chain.
- Performing audits and verifications as needed.
- Evaluation of the deliveries from the partners at DG2 and DG3, incl. technical evaluation and ranking of the capture projects.
- Performing own HSE activities as HAZID and HAZOP for the interface between capture export terminal and ship for CO_2 transport, and the CCS chain carbon footprint.
- Organizing risk-based quality assurance of deliveries (except the KS quality assurance).
- Developing and maintaining an overall project schedule.
- Coordinating the development of the interfaces between the various sub-projects, incl. management of a technical committee and an agreements committee.
- Advising and assisting MPE in commercial negotiations with the industrial partners.
- Analysing and managing project risk in line with recommendations given in NS-ISO 31000.
- Reporting to and preparing documentation for the project steering committee (led by MPE).
- Increasing the industrial partners' awareness of the risk of cross-subsidization.
- Coordinating and leading the work on benefit realization.

A small core team has been required from Gassnova to follow up on the study work from the feasibility study through FEED (organized as a small project team with traditional roles/disciplines such as project leader, project controller, HSE, technical experts, etc).

Key learning points

- Dividing the responsibility for the CCS chain between the industrial partners doing capture, transport and storage has been a pre-condition for success, and has allowed the emission source owners to develop their business cases without having to establish their own transport and storage solution.
- The state has accepted the cost and risk associated with uncertainties in the interface between capture and transport/storage. This is one of the key principles for the operating phase.
- To coordinate and facilitate the development of the CCS chain, it has been important for the state to retain the project integrator role via Gassnova.
- Establishing committees with participants from Gassnova and all the industrial partners has allowed free discussions on topics of common interest. It has been very useful in terms of aligning the CCS chain and has led to more efficient and predictable interaction between the partners.
- Managing the interface between capture and transport/storage has required a fine balance between widely differing company cultures and practices (major oil companies on the one hand and producers of commodities and heat/energy on the other). Different expectations concerning work processes, level of detail in deliverables, resource use, etc. have created frustration for all parties.

Project development in stages

The project has been developed according to best practice project management methodology for large industrial projects, as illustrated in Figure 1. To efficiently explore possibilities and make informed decisions at the right time as the project matures, working through a well proven model is very helpful. Each phase in the project development has defined deliverables and ends at a decision gate (DG) before moving into the next phase. To ensure that the deliverables from the different industrial partners aligned with Gassnova's expectations, guidelines from the American Association of Cost Engineers (AACE) were used as a frame of reference. Gassnova and the industrial partners have used similar project development models, although the name of each phase and the decision gate (DG) numbering differs slightly.

At each decision gate, every partner has had the chance to abort their own project; however, the overall decision to provide state aid for the next phase has resided with the government.

The overall timeline for the project is shown in Figure 2.

As shown in Figure 2, different parts of the project have been developed according to somewhat different time-schedules. In particular, the development of the transport and storage sub-project has taken more time than originally envisioned. A change of storage location within the Hordaland Platform region from Smeaheia to Aurora and an unforeseen need for a test well to verify reservoir properties prolonged the concept study and the FEED study, respectively.

Key learning points

- The traditional stage gate project development model shown in Figure 1 has been applied with success. Thanks to the widespread knowledge of this model, all parties involved in the project have been able to relate to the typical scope of work, deliverables, accuracy of cost estimates, etc. This has generally helped maintaining a high quality in deliverables and has made cooperation between different companies easier.

- It was necessary to use a common frame of reference for the objective of each project development phase. Using the recommended practices from AACE has been successful, and the "Recommended Practice for Cost Estimation Classification" (18R-97) has filled this purpose very well.

- When developing geological storage for CO_2 it may be difficult to use the typical work processes major oil & gas companies normally follow when they develop projects. The Northern Lights partnership had to adapt its development model to reflect differences from its traditional projects given that there are no valuable resources in the ground, no business model or market thus far, etc.

- With independent sub-projects following different schedules and project external processes related to the state aid, it has been challenging to develop the project along a typical industrial path. A high number of critical decisions have been made throughout the project development; decisions that often have been mutually dependent on each other and taken by different companies or by the government. This has required transparency and flexibility from the involved parties but has still led to unplanned periods with lower activity.

- According to established industrial practice, selection of technical solutions is closely connected to cost and commercial aspects, and the project framework should therefore be developed as early as possible in the project development process. However, this was not possible for this project due to the commercial and regulatory immaturity of CCS. The staged development has in itself been instrumental in the stepwise establishment of trust between the government and the industry, allowing both technical and commercial aspects to mature in parallel.

Stage gate project development model

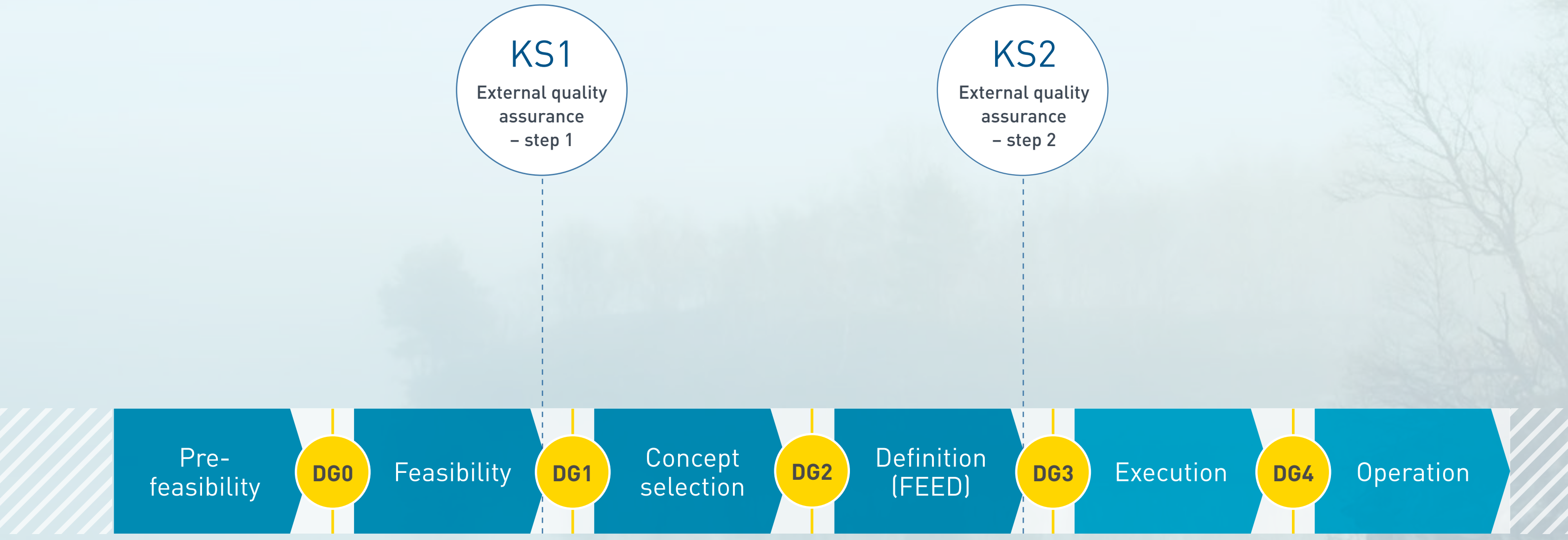


Figure 1: Stage gate project development model, also showing the timing of the external quality assurance required by large public projects in Norway (KS1 and KS2).

Overall timeline

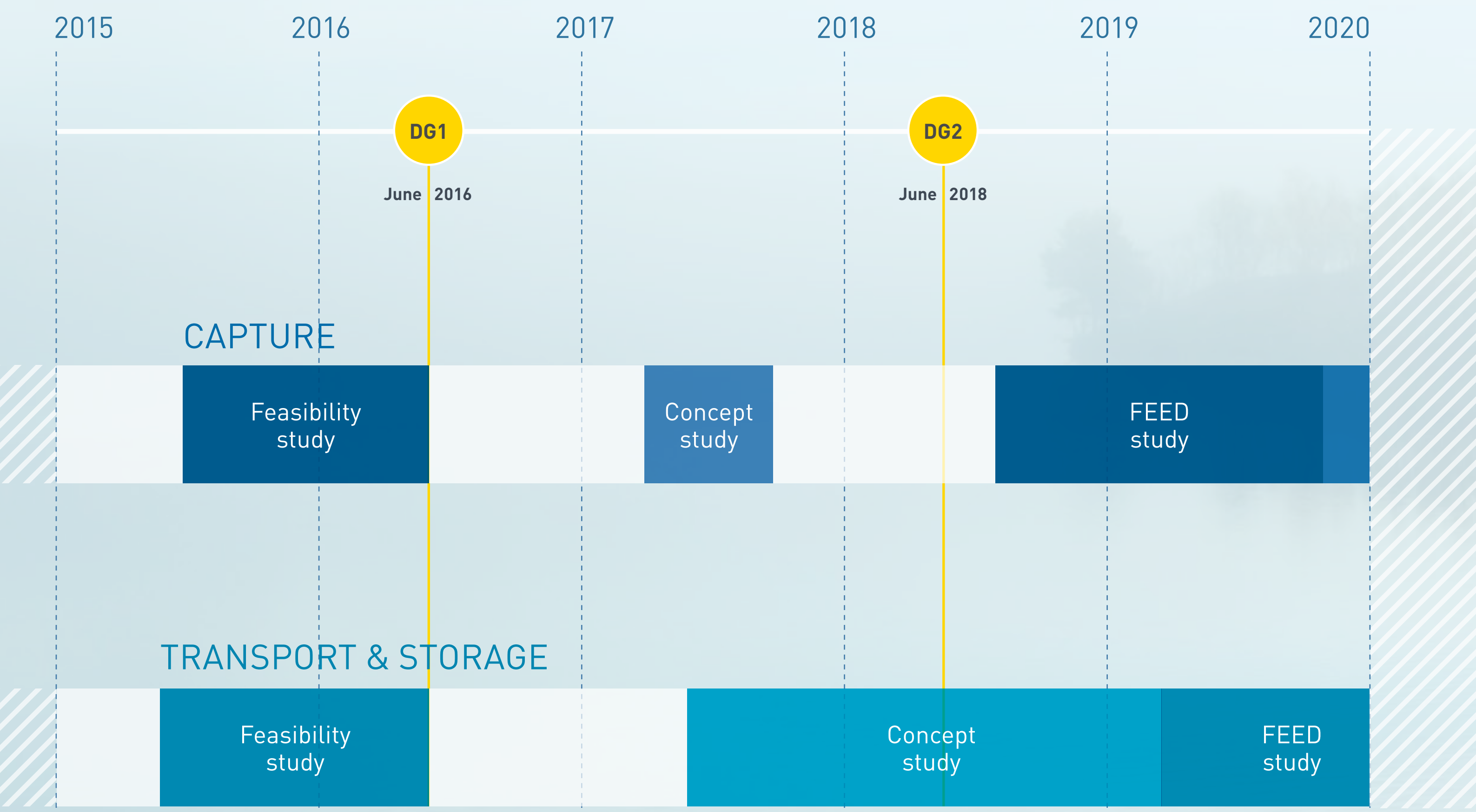
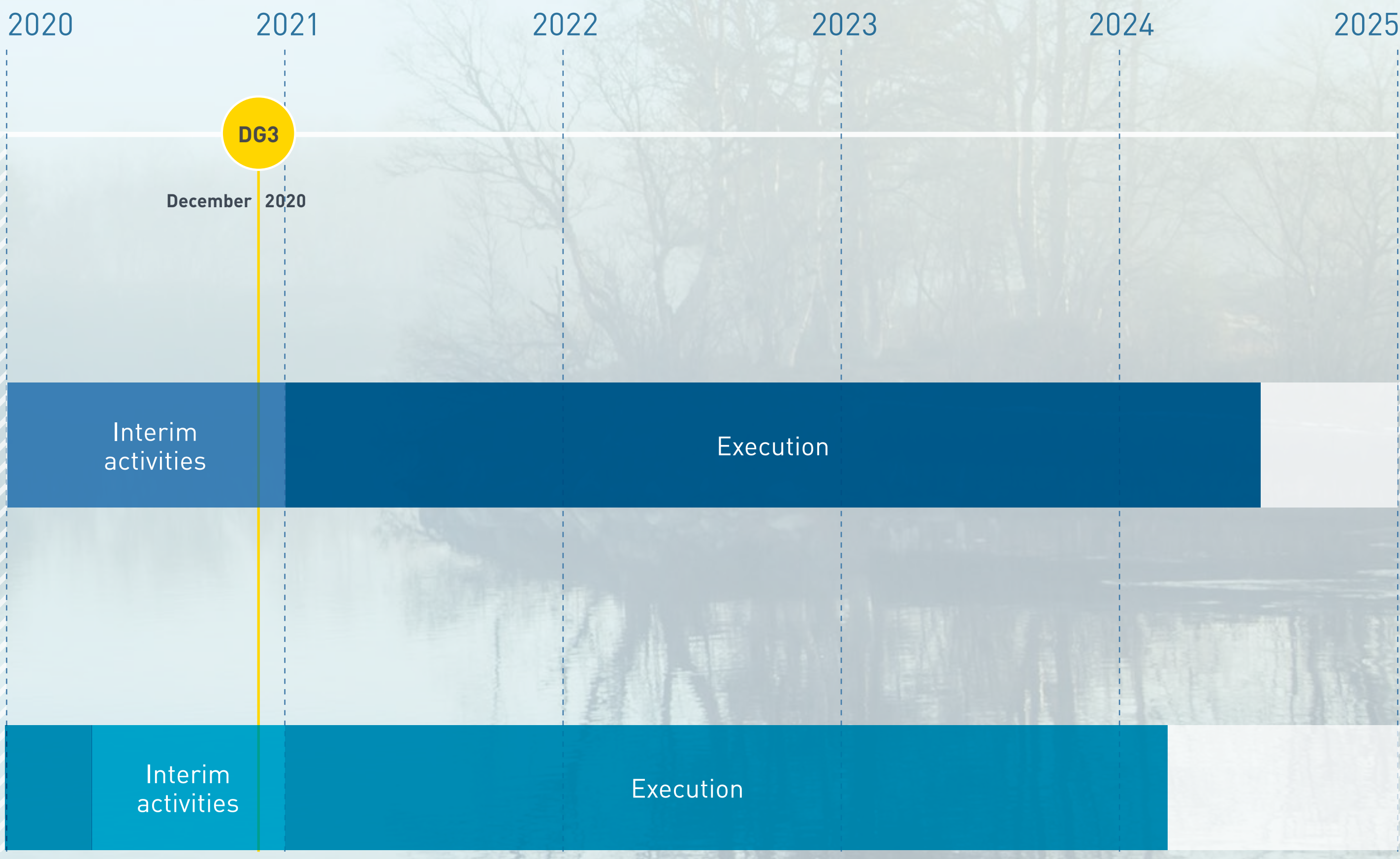


Figure 2: Overall timeline of the project, from start of the pre-feasibility phase to start of operating phase.


2020
2021
2022
2023
2024
2025
DG3
December 2020
Interim activities
Execution
Interim activities
Execution

The industrial partners

Based on the Norwegian Environment Agency's list of emissions of CO_2 from land-based industry, Gassnova performed a study in 2012 mapping the potential capture of CO_2 from existing Norwegian emission sources. Around 30-35 sources were emitting more than 100,000 tonnes of CO_2 per year, comprising oil refineries, gas processing plants, petrochemical plants, cement factories, metal processing plants, etc. A selection of potential future emission sources was also considered. In line with the Global CCS Institute's definition of "large scale", 400,000 tonnes of CO_2 per year was set as the least amount of CO_2 to be captured. This reduced the number of relevant emission sources to 14.

> Through a dialogue with their owners, these emission sources were further screened based on technical, commercial, and financial aspects, including the owner's interest and rationale for engaging in the capture of CO_2.

The final list of emission sources that were considered relevant for the capture of CO_2 was a short one: Yara's ammonia plant at Herøya and Norcem's cement factory in Brevik were the only existing plants, plus a few potential future plants.

From 2014, owners of *existing* land-based emission sources in Norway have been invited to carry out the necessary studies to mature CO_2 capture plants, starting with pre-feasibility studies, followed by feasibility studies and subsequently combined concept and FEED studies. Apart from Yara and Norcem, only Fortum Oslo Varme (then known as Energigjenvinningsetaten and owned by the City of Oslo) tendered for these studies. All three companies were awarded study contracts with Gassnova. The CO_2 emissions from Fortum Oslo Varme's waste-to-energy plant at Klemetsrud were lower than 400,000 tonnes per year, however Energigjenvinningsetaten carried out a pre-feasibility study on their own initiative and at their own expense. The study showed that capture of CO_2 at Klemetsrud have the potential to generate valuable learning in line with the government's goals. Plans to ramp up the waste incineration capacity were also presented, increasing the amount of CO_2 to be captured to 400,000 tonnes per year.

After the concept studies on capture was completed it was decided that Yara where not continuing with a FEED study on capture from the ammonia plant at Herøya, mainly because the future production volume of ammonia is uncertain and the technical solutions had limited learning effect for others.

The development of the CO_2 storage had a different start than for capture, as the number of potential storage operators in Norway is limited. Following a public procurement process, all companies qualified as operators for petroleum operations on the Norwegian continental shelf were allowed to tender for the feasibility study on CO_2 storage. Only Statoil (now Equinor) submitted a tender and was consequently awarded the study agreement. Following the completion of the feasibility phase, qualified operators were invited to tender for combined concept and FEED studies on the storage of CO_2. Statoil and Total submitted tenders, but only Statoil was awarded a contract. Shortly after the award, Statoil, Shell and Total formed the Northern Lights partnership.

> From the initial stages of the project, transport of CO_2 has been viewed as mature and available for procurement in a functioning market.

Through the feasibility phase and concept selection phase, Gassco had the responsibility as a neutral party to define and coordinate the study work. After completing their concept study, the responsibility for the transport sub-project was transferred to Northern Lights, through an option in the study agreement.

Key learning points

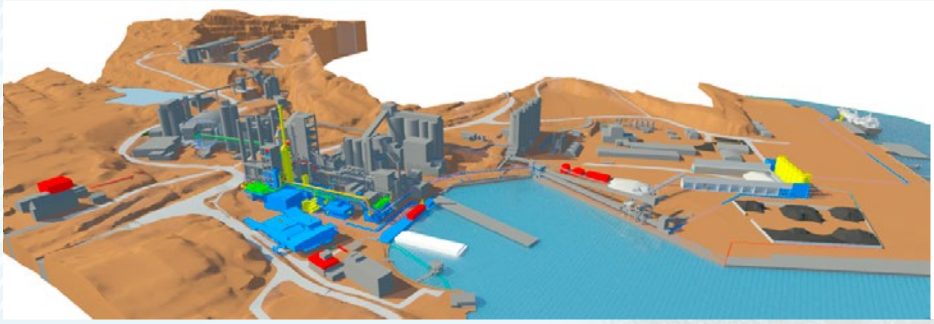
- Except for Yara, all the industrial partners involved in the early phases of the project are still involved and have taken their FID's. Given the objective of the project, the strategy to map all existing emission sources in Norway and aim for capture from the sources of significant size and with a strong self-interest in doing CCS, has been successful.

- The establishment of the Northern Lights partnership by Equinor, Shell and Total has given access to world-class expertise, including experience from ongoing commercial CCS operations. The Northern Lights partnership also represents companies that are in a good position to bring the learnings from the project into new projects.

- Based on Gassnova's experience from the early mapping and screening, typical reasons why the industry might consider CO_2 capture unattractive are:

    - Cost of capture perceived as very high compared to alternatives (e.g. CO_2 quotas has been available at very low cost)
    - Unclear what kind of climate regulations and policies that will be set out for industry in the future and when
    - Investment barriers and risks related to the whole CCS chain. Each part of the CCS chain is dependent on successful development and operation of the other parts of the chain. The value of capturing CO_2 is low or even negative if there is no transport and storage operator available to store the CO_2 according to relevant regulations
    - Low CO_2 concentration in exhaust gas or many dispersed CO_2 emission sources (e.g. aluminium production)
    - Uncertainty regarding business model (divided costs between the industry and the state)

3D illustrations



Norcem's existing plant (in grey) and the planned capture facility (in colors).

Source: Norcem AS

Fortum Oslo Varme's existing plant (in grey) and the planned capture facility (in colors).

Source: Fortum Oslo Varme AS

Northern Lights' planned CO_2 receiving terminal.

Source: Equinor ASA

State aid

As documented in several reports, several barriers make investments in CCS unattractive for industrial parties. To obtain early industrial CCS investments, cooperation between industry and the public sector is needed, together with public financial support. Public-private cooperation has been important in handling specific investment barriers for CCS, especially related to cross-chain risks and overcoming an unfit and immature regulatory framework.

> To facilitate this cooperation a project development process in stages has built trust between the private and public partners has been important.

CCS also needs state aid to compensate for market failures related to climate policy (the cost to industry of CO_2 emissions is less than the socio-economic cost of these emissions) and technology development.

It is anticipated that CCS would require less technology-specific policy in the future as technology and markets evolve.

The need for state aid has raised several issues related to:

1. Competition rules in the European Economic Area
2. Norwegian legislation on public procurement
3. Longer time between the project development phases to allow for necessary quality assurance and decisions on the government's side.

Key learning points

- Relying heavily on state aid, it has been important to make sure that the industrial partners understand the consequences and plan accordingly. Conducting procurement according to public procurement laws and obtaining approval from the ESA will require time and resources that are unfamiliar for most industrial projects. It is advisable to make legal assessments, to study relevant regulations, and to establish a dialogue with ESA as early as possible.
- With a significant share of state aid it is a risk for the government that the industrial partners would design their CCS-facilities with excessive requirements to technical quality and performance (known as "gold plating"). Despite this, the CCS chain is considered to have an appropriate design. Factors like the competition between the capture projects, reasonable technical requirements from the state, and a strong desire with all parties to keep the cost down have been important in this respect.


CO2
TECHNOLOGY
CENTRE
MONGSTAD

Governmental contract strategies

One of the key principles for the governmental contract strategy is that the industrial partners in the project are most qualified to take full responsibility for planning, constructing and operating their part of the CCS chain. It was therefore decided early on to run the concept and FEED studies as a competition for state aid, with an option to carry out detailed engineering, construction and operation. In 2016, the feasibility studies were completed, and the competition for combined concept and FEED studies was announced later the same year.

The overall contract strategy from the government's side is based on competition between the potential capture operators all the way up to completion of FEED, with the storage operator chosen before the start of the combined concept and FEED studies. Transport of CO_2 by ship has been assumed to be a service that is available on a commercial basis in a functioning market. In order to reduce the number of interfaces in the project, the responsibility for the transport sub-project was transferred to Northern Lights after Gassco completed its concept study in late 2017.

Negotiations on the terms of the state support agreement for the construction and operation of capture, and transport/storage of CO_2 started in 2017 in parallel with the concept studies. The MPE conducted negotiations with each industrial partner on behalf of the government. Establishing and agreeing on commercial terms proved to be complex and more time-consuming than anticipated, and the negotiations concluded in the first half of 2020.

> Within the frames of the support agreement, each industrial partner has the sole responsibility to perform detail engineering, construction, start-up and operation of their part of the CCS chain.

The government has developed the state support agreements in such a way as to give the partners incentives to act in line with industrial practices throughout the construction and operating phases. However, the agreements allow the government to be hands-on during the follow-up of the project.

> The risks and costs are split between the partners and the state, with significant contributions from the partners.

One of the main principles behind the state support agreement is that the state will provide funding to cover part of the actual costs, but only up to an agreed limit (corresponding to the P85 estimates). By capturing and storing CO_2, the emissions from the capture plants will be significantly reduced, which will allow the capture operators to sell surplus CO_2 quotas in the EU ETS. The state will also compensate the capture operators for the CO_2 emissions that have been avoided but that are not covered by the EU ETS, up to 400,000 tonnes of CO_2 per year. Since Northern Lights does not get any additional compensation to handle the CO_2 from Norcem and FOV, they will have to sell their surplus capacity to third-party paying customers in order to generate an income.

Key learning points

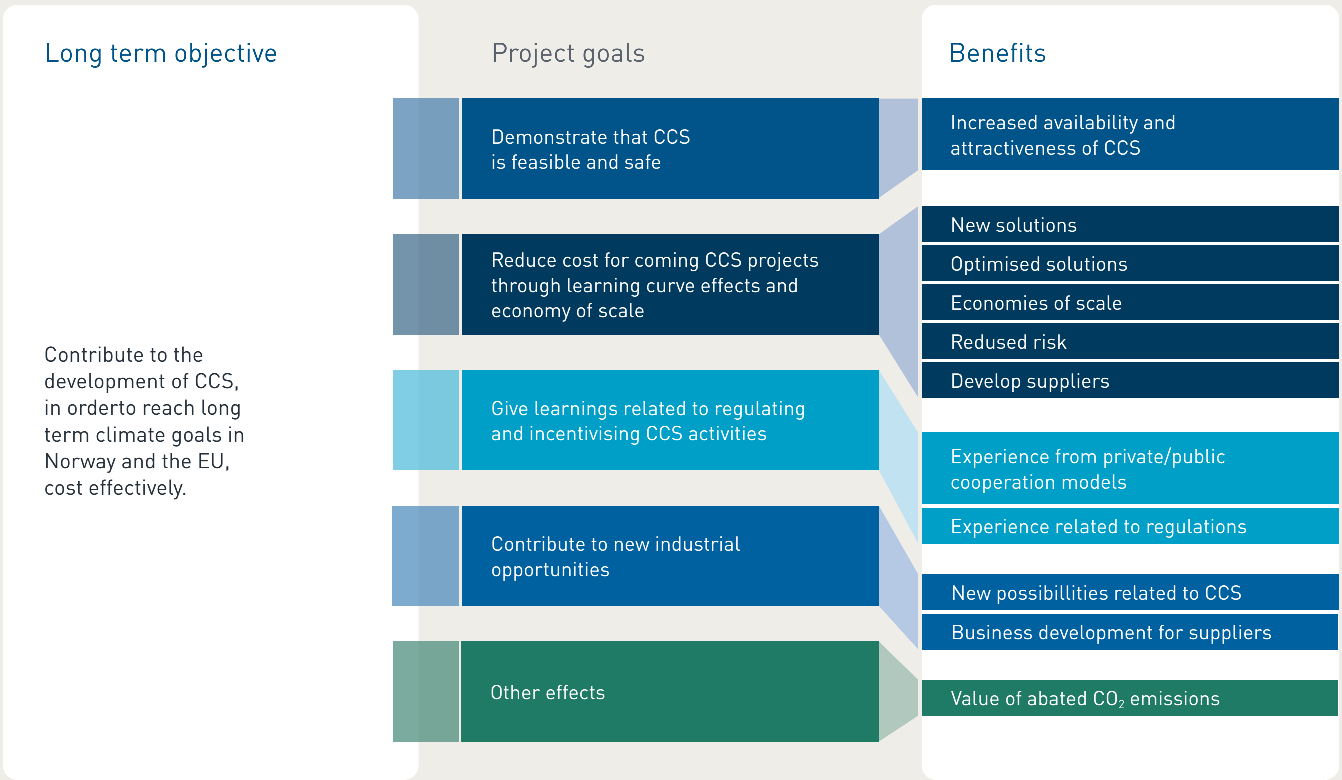
- It has been necessary for the state to accept that the industrial partners will only enter a contractual relationship directly with the state, with no obligations towards the other partners in the CCS chain. The key operational principles that will govern the cooperation between the industrial partners are detailed out in a separate appendix to the state support agreement. The state has accepted to carry the risks associated with the operational cooperation between the partners and the potential extra costs incurred from potential delay of any of the sub-projects.
- The competitive element between FOV and Norcem has added value in several ways: Capture from industries with different potential to generate learning have been explored thoroughly; the quality of the deliveries from the competing sub-projects has been high; and the state got a stronger position in the negotiations.
- When negotiating the terms of the study agreement for the concept and FEED studies on the transport and storage elements, the competition between several companies resulted in a larger financial contribution to the study work.
- Since the commercial negotiations and FEED studies were conducted in parallel, the industrial partners had to set the design performance of their facilities without complete knowledge of the commercial implications. It is advisable to settle the commercial mechanisms earlier, if possible.
- The competition between the capture sub-projects required strict formal structures to be in place and forced Gassnova to be careful in its feedback to the competing partners to ensure equal treatment. The competitive element has constrained open dialogue between the partners and made it hard to capitalize on potential synergies across the CCS chain. These are negative aspects of the competition, which should be taken into consideration when developing the contract strategies at a high level.

Benefit realization

The plan to work on "benefit realization" alongside the ordinary project development gained traction as the first step of the external quality assurance (KS1) in 2016 concluded that the benefit side of the project was unclear and that they feared that no projects would gain from the learnings of this project as it was unlikely that other CCS projects would follow this project.

Gassnova was tasked with leading and coordinating a programme to maximize the benefit and value creation from the project. Benefit realization is a systematic work process to ensure that the benefits of the project is understood and that value-adding activities are carried out as the project matures and is realized. This work was led by Gassnova, with strong contributions from all the industrial partners and activities in the MPE. Gassnova will continue to coordinate this work in the realization phase.

Four main groups of benefits from the project have been identified: the demonstration effect, the cost reduction effect on subsequent projects, the effect of new business opportunities, and the effect of reduced CO_2 emissions.



Key learning points

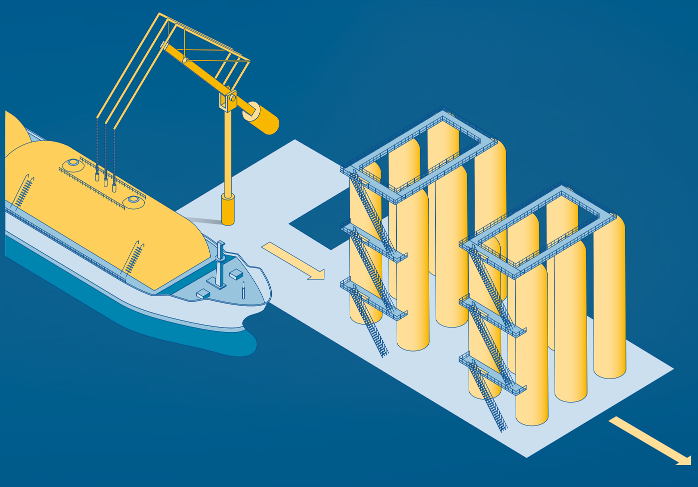
- The benefit realization concept has been important to developing a common understanding of what the state wants to achieve through the project. The concept has been an important framework where all project parties (both industrial and public sector) have identified and carried out value-adding activities. This has been recognized in the external quality assurance report (KS2).
- When the business development of an industrial partner aligns with the benefits realization work the results are strong. The work that Northern Light's business development team has done has resulted in an impressive plan for developing the market and the infrastructure.
- The benefit realization concept has been relatively new to all the project partners. It has sometimes therefore been misunderstood as a set of activities to advertise the project or CCS in general.

02

PROJECT DEVELOPMENT

Developing a CCS chain with CO_2 capture, transport by ship and geological storage is technically feasible and safe. Competent contractors and suppliers can be mobilized and a CCS chain can be developed with limited use of new technology.

The London Protocol has for years been a barrier for cross-border transport and storage of CO_2. However, in 2019 the parties to the London Protocol agreed on a temporary amendment allowing export of CO_2 for the purpose of storage offshore. Aside from this, no regulatory showstoppers have been identified so far.



Design Basis

As a tool to frame the overall project and the various sub-projects along the CCS chain, Gassnova has developed and maintained an overall Design Basis document.

> The Design Basis has been developed in close cooperation with the industrial partners following a philosophy of keeping the number of requirements to a minimum.

This allows freedom for each sub-project, while also ensuring that the sub-projects will fit together as a whole to make up the CCS chain. Few requirements leave things to the interface development performed jointly by the partners, which is likely to give the most "industrial" solutions.

Specifically, the parameters that have been governed by the Design Basis during the FEED studies are:

- Target CO_2 capture rate of 400,000 tonnes of CO_2 per year per capture site
- Technical design life (25 years)
- Placement of the battery limit between capture and transport/storage
- Overall philosophies for HSE, design and operation
- CO_2 specification and export conditions at the capture plant export terminals
- Online measurement of impurities in CO_2 during export from capture site
- Dimensioning criterion for the interim storage tank capacity at the capture plant export terminals
- Maximum ship dimensions for selection of berth
- Capacity of onshore power supply
- Transport ship propulsion type
- Design capacity of CO_2 receiving terminal (1,500,000 tonnes of CO_2 per year)
- Vapour return system

Due to a lack of experience from comparable CCS chains around the world, Gassnova chose not to develop firm requirements for availability or uptime for the total CCS chain or for each part of the chain. The only exception is that capture plant availability should be above 85%, which is not very challenging. Based on the estimates from the FEED studies, the overall availability of the CCS chain is expected to be around 92-93%.

Key learning points

- The philosophy of keeping the number of requirements as low as possible in the overall Design Basis has worked as intended, allowing the sub-projects to develop as each partner has seen fit. This has led to few significant changes and has maximized the alignment between the project and each partner.
- Transport of CO_2 in a liquid state implicitly adds purification of the CO_2 "for free", as many impurities are naturally removed in the liquefaction process. Studies show that relaxing the specification would only give minor savings in capture costs. The CO_2 specification for a CCS chain based on transport in gaseous/dense phase will require a different specification.
- Introducing requirements for overall availability, as well as the availability of each part of the CCS chain, would have made it easier for the partners to optimize the design of their facilities. However, this "top-down" approach would also introduce a risk of setting the wrong target, as the development of a CCS chain does not yet have any clear business case.

Capture technology selection

The technology used for capturing CO_2 from a flue gas is often unproven or previously used on different gases or under different conditions.

Selection of the right technology to use is a central choice for a CCS project and depends on many factors such as the characteristics of the CO_2 emission source, available utilities, whether a large or small fraction of the CO_2 is to be captured, etc.

The maturity of available technologies is also an important factor since qualification of new technology always is uncertain and requires use of additional resources during the project development (see chapter 03).

To minimize net present cost or max net present value, will generally be the objective when selecting technology. Constraints may be the allowable emissions of degraded amine products, available capacity in the downstream CCS chain, etc. However, in practice it may prove difficult to produce reliable cost estimates if the technology selection is done at an early stage in the project. Other objectives besides low cost may also be relevant. Both Fortum Oslo Varme, Norcem and Yara put emphasis on avoiding time and resource demanding qualification programs when selecting capture technology.

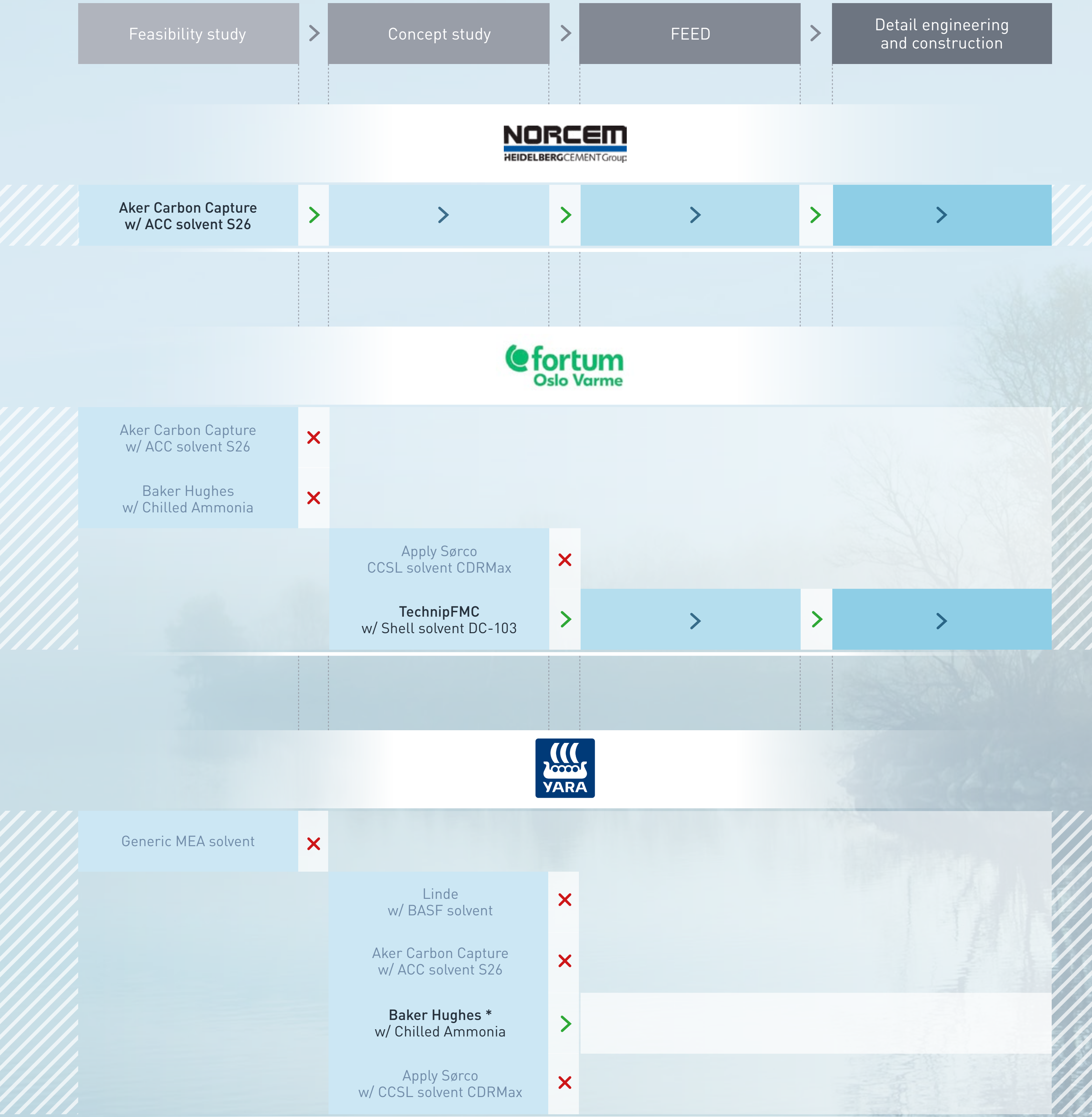
When selecting capture technology, it is important to consider aspects like:

- Access to heat and electricity.
- Techno-economic assessment covering different types of technologies & technical solutions (e.g. change in operating conditions of host plant and required pre-treatment of flue gas). Even within the category of amine technology there are many amines with different pros & cons.
- For amine technology it is particularly important to establish reliable predictions for expected emissions of amines and amine degradation products to air. Remember that each amine is different and that countries have different requirements to what is acceptable emissions!
- Conditioning for transport and/or storage (liquefaction, compression, purification, etc.) is a significant part of the CCS chain and is affected by the choice of capture technology.
- Different technologies may favour partial or full capture.
- Means of transport to storage site (if not already given as a boundary condition).
- Pros and cons of using proprietary technology, which will heavily influence later procurement strategies.
- Use of unproven or new technology will add risk and uncertainty and will require technology qualification. Experiences from design and operation of relevant references are key elements when assessing a technology.
- Ability of technology provider to issue and back up performance guarantees.

Fortum Oslo Varme, Norcem, and Yara put different weightings on these points (and other criteria that they consider important). This is reflected by the type of technology selected and the timing of the selection, as shown in Figure 3.

Key learning points

- When planning to use amine technology for capture, it is important to quantify the emissions of potentially carcinogenic substances into the air and to model how these are dispersed in the surrounding environment. It is advisable to involve personnel and suppliers with specific competence and experience with CO_2 capture at an early stage, including understanding of local environmental regulations. A "toolbox" for amine technology has been developed by Gassnova and is available at https://ccsnorway.com/
- The capture technology selection process is like other major decisions that are typically taken in the concept selection phase. There are no major differences compared to other conceptual decisions, but certain aspects should be kept in mind (as listed above).
- Selecting capture technology before the concept selection phase will narrow down the available choices too early, restriction options in the next phase of the project. This is likely to reduce the overall value of the project by increasing the cost or reducing the benefits.
- When considering using proprietary capture technology, it is important to acknowledge that this will make it challenging to obtain competitive bids for your project in a later stage. This is particularly relevant if the technology provider has an exclusive partnership with, or is owned by, an engineering contractor. It is highly advisable to early develop a contract strategy that ensures competition for the detailed engineering and construction of the major parts of the scope. The fact that Fortum Oslo Varme and Norcem have competed to be part of the CCS chain has partly compensated for the lack of competition on the main contracts within their own scope.



(*) Yara studied capture of CO_2 from different emission sources in their ammonia plant, both from pressurized process gas and from exhaust gas. Capture of CO_2 from pressurized process gas is considered a well proven technology that is widely used in chemical industry. Only the technologies studied for the exhaust gas alternative is therefore shown here. The Chilled Ammonia technology from Baker Hughes was the preferred technology after completed concept studies, but due to Yara leaving the project in 2018 a FEED study was never executed.

Figure 3: Different engineering contractor and technology provider options explored by the industrial partners.

Maturation of the underground storage

The potential for geological storage of CO_2 in Norway is concentrated on the Norwegian Continental Shelf due to lack of suitable geology on land. The Norwegian Petroleum Directorate has published an extensive description of this potential in a CO_2 Storage Atlas (2014) that maps out the options available in depleted hydrocarbon fields and saline aquifers.

When maturing a potential CO_2 storage site in Norway the focus has been on:

- assessment of the entire storage complex and its boundaries;
- assessment of the integrity of the seal;
- simulations of CO_2-plume migration within the storage complex;
- assessment of the pressure development in the reservoir;
- how the dissolution of CO_2 evolves in the reservoir;
- how to handle possible pressure increase far above initial pressure, and
- time perspective of thousands of years.

Potential sites with limited data availability or low degree of maturation, long distance to shore, or uncertain seal properties were excluded from further investigation. This is in line with the ISO standard for geological storage of CO_2 (ISO 27914, 2017) that Norway helped to develop.

> The Northern Lights storage site within the area referred to as Aurora will be the third CO_2 storage site to be developed in Norway. The CO_2 reservoir selection processes for the Sleipner and Snøhvit fields were constrained by the field development plans for their associated petroleum projects, but the selection process for Northern Lights has been different since it is not tied to petroleum field development.

The selection process carried out by Northern Lights is the most recent stage in a site screening process that began on the Norwegian continental shelf in 2007 and will carry on into the future as additional CO_2 storage sites are developed by Northern Lights and other operators. The key stages in this site screening process are described in chronological order.

Key learning points

- The choice of CO_2 storage site was changed during the concept study. This caused a delay to the concept study and has generated additional pipeline cost for the project by moving to the Aurora area, further offshore. The decision was justified with new information that came to light during the study work which increased the concerns about possible pressure connection with the Troll field. A key learning point is the need for flexibility in the concept selection phase and the availability of one or more back-up storage locations that have been de-risked to some extent already, as was the case with the Aurora area.
- This storage site was chosen to minimise potential legal and commercial complications by storing CO_2 in a saline aquifer outside of existing hydrocarbon licence areas. This has been a critical success factor in order to complete the concept and FEED studies in a timely manner. The re-use of depleted oil and gas fields may also generate additional cost related to the treatment of legacy wells.
- Longship is being developed within the legal framework of Norwegian CO_2 storage regulations and these have proven to be fit for purpose. The risk management approach taken by the project team has been broadly consistent with that described by ISO 27914:2017 'Carbon dioxide capture, transportation and geological storage – Geological storage'. This is recommended as a reference source for managing risks and opportunities associated with CO_2 storage.

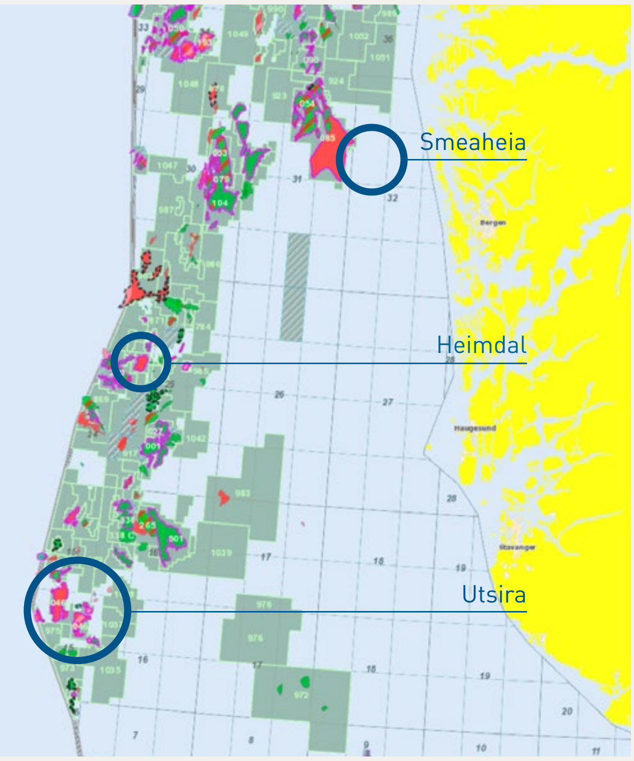


Figure 4: Three areas studied in the feasibility study completed in 2016.

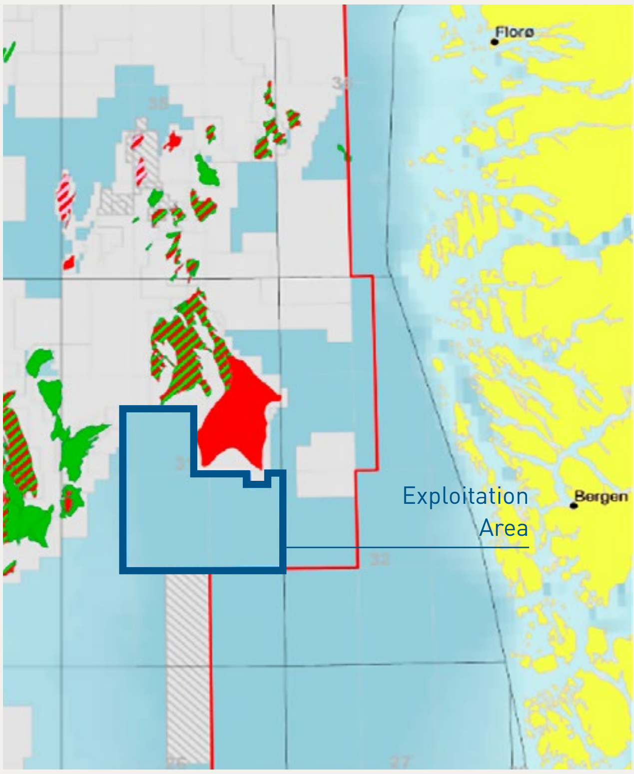


Figure 5: Map showing the Exploitation Area in blue.

2007	The Norwegian Petroleum Directorate (NPD) began mapping CO_2 storage resources. A report prepared for the MPE by Gassnova, Gassco and NPD concluded that CO_2 can be stored safely offshore Norway.
2010	One North Sea Report presents a study into North Sea cross-border CO_2 transport and storage where the potential for CO_2 emissions from the industry around the North Sea Basin and potential storage sites capacity was analysed.
2011	MPE invited the industry to nominate promising areas in the North Sea and Norwegian Sea for exploration for potential reservoirs for permanent storage of CO_2 from the Mongstad refinery.
2012	Gassnova presented a study to the MPE after analysis of the Johansen Formation and the Upper Jurassic Sognefjord Formation.
2013	The Government pointed out a new direction for CCS. The development of full-scale CO_2-capture at Mongstad was discontinued.
2014	The Norwegian regulations for CO_2 transport and storage were passed into law and the NPD published a CO_2 Storage Atlas for the entire Norwegian continental shelf.
2015	Gassnova delivered a pre-feasibility study for a new CCS value-chain in Norway to the MPE. Gassnova was granted funding to initiate a series of CCS feasibility studies based on results of the pre-feasibility study.
2016	MPE published the results of the feasibility studies carried out by Gassnova in partnership with Gassco and the industrial partners. These confirmed that it would be possible realize a full-scale CCS project in Norway and through Gassnova MPE initiated concept and FEED studies with the industrial partners. Equinor proposed three possible areas for CO_2 storage (see Figure 4) and recommended one of them, Smeaheia, for further study.
2017	Equinor formed the Northern Lights partnership with Shell and Total. Gassnova coordinated the studies with the two CO_2 capture sites. Northern Lights decided to change storage location within the Horda Platform region from Smeaheia area east of Troll to the Johansen Formation south of Troll and made use of previous state funded work and seismic data from 2008-2014. The relevant reservoir intervals in the Smeaheia area were found to have a possible pressure connection with the giant Troll oil and gas field that could negatively affect the density of CO_2 stored there in the long term and this risk is now being investigated further by Equinor research.
2018	MPE announced the first exploitation licensing for CO_2 storage within area south of the Troll field. This area included the area of interest for CO_2 storage in the Johansen Formation.
2019	MPE granted Equinor an exploitation permit for CO_2 storage, EL001 on behalf of Northern Lights, as shown in Figure 5. This is the area referred to as Aurora.
2020	The first exploration well, 31/5-7, Eos, was drilled in the licence. The well showed good potential for CO_2 storage. The Northern Lights partnership submitted a development plan for EL001 to MPE.

Energy input and carbon footprint

CCS is known to be energy-intensive, and without any heat integration on the capture side, the total energy input required by the Norwegian CCS chain would be around 1.2–1.5 MWh/tonne CO_2. About 2/3 of this is needed as heat, while the rest is electricity and fuel for the ship. The energy required for the ship transport and for storage is marginal compared with the energy input required for capture, in particular the amine capture process and downstream liquefaction facility.

> With efficient heat integration, as studied and developed by both Norcem and Fortum Oslo Varme, it has been possible to reduce the energy requirement for the chain by as much as 40-75%.

The diagrams Figure 6 and Figure 7, show the energy input along the CCS chain for both Norcem and Fortum Oslo Varme with and without energy saving from extensive integration. The heat integration can be done both between the production plant and capture process and between the capture process and liquefaction plant. Due to the differing nature of the Norcem and Fortum Oslo Varme production plants it is not possible for Fortum Oslo Varme to extract as much energy from the waste-to-energy plant as Norcem can from the cement production.

In order to verify that Longship will store much more CO_2 than what will be emitted from the construction and operation of the chain, the carbon footprint was calculated. The carbon footprint is expressed as the CO_2 that is emitted in order to capture, transport and store one tonne of CO_2, taking the whole lifetime of the project into consideration. The main results are shown in Table 1. A dedicated report has been published by Gassnova* and an article with updated results will be published for the conference GHGT-15.

A third party developed an efficient setup for collecting the necessary input data from the project, following ISO 14040 "Life Cycle Analysis – principles and framework" and ISO 14044 "Life Cycle Analysis – requirements and guidelines". For each building block in the CCS chain, all project phases were included, from construction to decommissioning and post-closure of the storage. For each phase, the CO_2 emissions from the use of fuel, energy, chemicals, materials and transport were calculated.

The main reason to calculate the carbon footprint of Longship was to document that the footprint will be low and very much lower than the amount of CO_2 stored. In fact, the calculations show that the carbon footprint will be lower for than other CCS projects reported in the literature**. This can be attributed to extensive use of waste heat, Norwegian electricity mix with low CO_2 footprint, and a high focus on using low footprint energy and fuel alternatives wherever possible.

Norcem has a lower carbon footprint than Fortum Oslo Varme, mainly due to the opportunity to utilize the excess heat from the cement production. At Fortum Oslo Varme's waste-to-energy plant the heat is already used to produce electricity and provide district heating, which have prompted the use of heat pumps to compensate for the heat needed in the capture process.

Key learning points

- The capture plant has by far the biggest energy input requirement in the CCS chain. Since the CO_2 will be transported and injected in liquid form, the transport and storage parts of the chain only require a few percentages of the total energy input.
- For capture plants efficient heat integration is crucial, and it is highly recommended to perform detailed studies to find the optimum degree of integration. Both integration with the host plant and between the different parts of the capture plant should be investigated.

* A dedicated report on the CO_2 footprint as calculated after the FEED studies is available at https://ccsnorway.com/

** R. M. Cuellar-Franca and A. Azapagic, Carbon capture, storage and utilization technologies: A critical analysis and comparison of their life cycle environmental impacts, Journal of CO_2 utilization 9, 2015, p. 82-102.

Table 1: Calculated carbon footprint of CCS chains with one capture plant (at Norcem or Fortum Oslo Varme), or two capture plants (expressed as tonnes CO_2 emitted/tonnes stored).

	CCS chain		
	with Norcem	with Fortum Oslo Varme	with Norcem and Fortum Oslo Varme
25 years operation + Utilization of the CO_2 receiving terminal capacity of 1,500,000 tonnes CO_2/year	0.047	0.061	0.056
10 years operation + Utilization of receiving terminal capacity of 400,000 or 800,000 tonnes CO_2/year	0.087	0.099	0.079

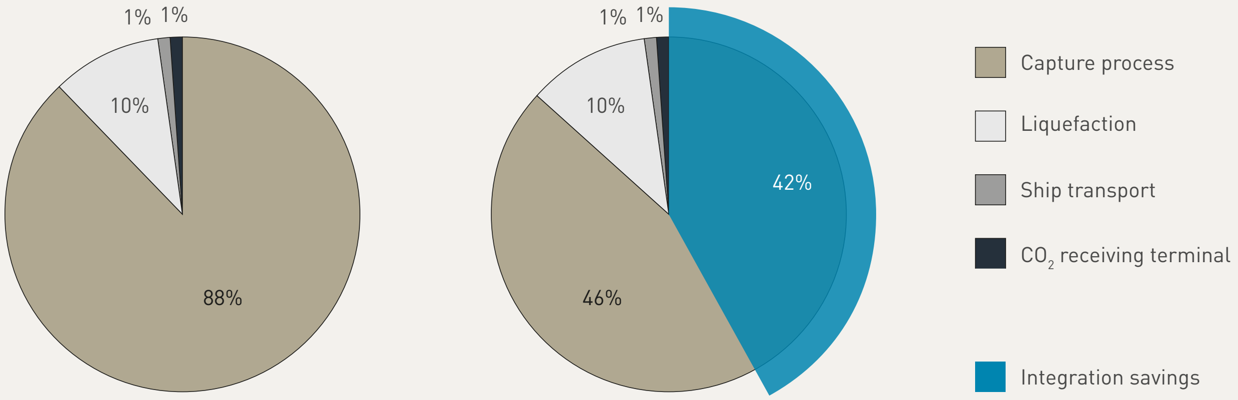


Figure 6: Distribution of the required energy input along the CCS chain with single capture plant at Fortum Oslo Varme. The left diagram shows energy input without any heat integration while the right diagram shows the energy input with heat integration.

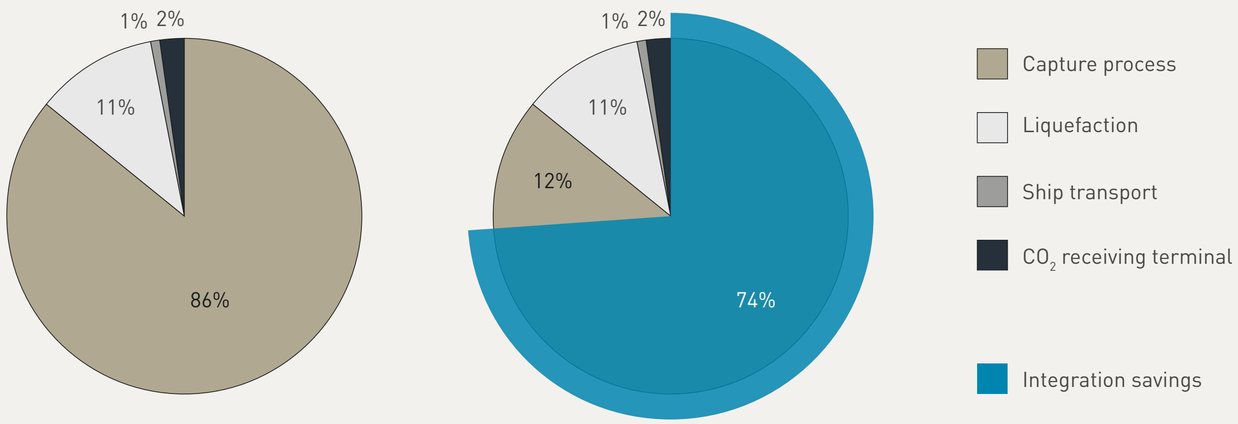


Figure 7: Distribution of the required energy input along the CCS chain with single capture plant at Norcem. The left diagram shows energy input without any heat integration while the right diagram shows the energy input with heat integration.

Regulations

As CCS deployment is still at an early stage, government agencies and regulatory authorities in most countries have limited experience with CCS projects. For the transport and storage part in particular, novel CCS regulations and existing regulations applied in the context of CCS for the first time have triggered the need for additional efforts, both from the project and from the authorities. In order to avoid delays it has been important to keep the dialogue between the parties involved transparent and open.

> The industrial partners and Gassnova have worked closely with the regulatory authorities to build knowledge and insight, identify potential issues early on, ensure alignment between governmental agencies, etc.

Observations concerning some of the regulations:

- The EU Directive on the geological storage of carbon dioxide (CCS Directive 2009/31/EC) was implemented in national Norwegian regulations in 2014 ("Forskrift om lagring og transport av CO_2 på sokkelen"). These CO_2 storage regulations were closely modelled on the existing petroleum regulations but is applied for the first time in Longship:
  - The CO_2 storage operations at the Sleipner and Snøhvit fields were already up and running when the new regulations came into place. These operations were found to be compliant and have continued to operate under the new rules.
  - The Longship storage site is the first CO_2 storage site in Norway to be fully permitted and licenced under the new rules. It will be returned to the state after its operational lifetime is complete and a period of subsequent compliance monitoring has established the long-term stability and fate of the CO_2 plume in the reservoir intervals.
  - Details surrounding the monitoring programme and the acceptance criteria that the government will apply with respect to long-term liability are defined within the Plan for Development and Operation (PDO) that Northern Lights has submitted to the Norwegian Petroleum Directorate. Although the timing and criteria for handing the storage back to the state remains to be agreed, sufficient clarity has been provided for the Northern Lights partners to take their FID's.
- EU ETS (Directive 2003/87/EC) are tailormade for CCS chains where the captured CO_2 is transferred to a storage facility either directly or via a pipeline. Other transport solutions, e.g. ship, truck or train, are not explicitly covered by the present regulation. In this project the regulation has been interpreted to mean that CO_2 is geologically stored when it is received at the onshore terminal. The European Commission has in a letter to the Norwegian Ministry of Climate and Environment confirmed that shipping of CO_2 is allowed under the ETS.
- The London Protocol aims to protect the marine environment by prohibiting unregulated dumping of waste, and it prohibits cross-border transport of CO_2, even for the purposes of geological storage offshore. This prohibits storage of CO_2 from European sources in Norway, with a damaging effect on the idea of shared storage infrastructure. To address this barrier, Norway and the Netherlands proposed a resolution that was accepted by the IMO in 2019, making it possible to establish agreements that allow cross-border transport of CO_2 for the purpose of geological storage.

Key learning points

- No regulatory showstoppers have been identified for Longship. Development of the capture plants follow regulatory processes that are well known to the industry. Due to the novel elements in the Norwegian implementation of the CCS Directive ("Lagringsforskriften"), it has been necessary for Northern Lights to work more closely than normal with the authorities to achieve effective and timely approval processes. Flexibility has been required from all parties involved.

- EU ETS regulation currently states that CO_2 must be transferred to a pipeline or facility directly connected to a geological storage for the capture operator to reduce the reported emissions. It has thus been necessary to regulate the change of ownership of the CO_2 at the interface between the capture plant and the ship in the state support agreements.

- If CO_2 is to be captured and stored in different countries, it is necessary to establish an agreement between the two countries involved in order to satisfy the London Protocol. It is important to address this issue as early as possible to ensure that the agreement is in place when the CO_2 is ready for cross-border transport.

- Norwegian fiscal regulations and EU ETS regulations seem to be sufficient to make a CCS chain operable in term of CO_2 metering. 1–1.5% accuracy in volume measurements is required, and because there is no loss of CO_2 from the transport ship, CO_2 received by the receiving terminal can be counted as "stored". The stored volume of CO_2 per ship load will be available for the capture site for yearly report on EU ETS.

Costs

The cost of maturing the capture part of the project from feasibility study through FEED study, including the waiting period after the concept study and the interim phase after FEED, amounts to 6–8% of the estimated investment cost for each capture plant (sum of state support and contributions from the industrial partners).

The estimated investment cost for each part of the chain is given in Table 2.

The investment cost of the capture plants spread across the various building blocks is shown in Figure 8 (where contingency and owners costs are assumed to be shared by all building blocks). The percentages given are typical for Fortum Oslo Varme's and Norcem's estimates with a maximum variation of +/- 5 percentage points.

The investment cost of transport and storage facilities spread across the various building blocks is shown in Figure 9 (where contingency, ownership costs, etc. are assumed to be shared by all building blocks).

For a CCS chain with both Fortum Oslo Varme and Norcem, the net present cost per tonne of CO_2 captured, transported and stored in the CCS chain will be NOK 1,280/tonne*. Slightly more than 50% can be attributed to transport and storage.

Utilizing the full capacity of the storage facilities will bring the net present cost per tonne down to around NOK 940/tonne. Development of similar CCS chains may bring the cost down even further**.

The initial net present cost per tonne is affected by the overall framing of the project. The following aspects contribute to a higher cost per tonne than can be expected for future CCS chains:

- The project is based on retrofitting existing CO_2 emission sources of relatively modest size.
- The distance between the capture sites and the storage site is long (700 km by sea).
- The overall concept is based on an onshore CO_2 receiving terminal with subsea pipeline to increase robustness and make it easier to develop a "storage hub".
- The project scope includes infrastructure for transport and storage that goes beyond what is needed to handle the CO_2 from Fortum Oslo Varme and Norcem only.
- The engineering contractors still have few references for the design and construction of CO_2 capture plants in operation, and the designs are tailor-made, which suggests that prices are higher than for common industrial plants.

Key learning points

- The extra capacity in the CO_2 pipeline and receiving terminal comes at a relatively low additional investment cost:
  - The cost of laying an offshore pipeline is similar up to a point where a larger pipe-laying vessel is needed. The increased cost of the pipeline itself is to some extent counteracted by less installation work needed (e.g. rock-dumping).
  - Due to the batch nature of the transport system, it is primarily the capacity of the injection pump at the CO_2 receiving terminal that needs to be increased to allow a higher throughput.
- Although the capture technology is an important building block in a CO_2 capture plant, it typically only represents a quarter of the total capture plant investment cost. Utility and support systems and preparation for transport (compression, liquefaction, conditioning and interim storeage) each represent as much as 33-34% of the capture plant investment cost and should receive attention early on.

* From the Figure 5-4 final KS2-report dated 24th June 2020. Calculated by the method from the Norwegian Environment Agency with 25-year horizon, Norcem and Fortum Oslo Varme combined.

** Potential for reduced costs for carbon capture, transport and storage value chains (CCS), DNV GL & Gassnova, 2019. Available at ccsnorway.com/

Table 2: Estimated investment cost for each part of the CCS chain (in MNOK-2020 represented by P50 estimates from KS2 report).

	Investment cost MNOK	Operating cost MNOK/year
Capture plant - Fortum Oslo Varme	4 090	224
Capture plant – Norcem	3 103	117
Transport and storage facilities – Northern Lights (*)	7 300	364
(*) These costs include one injection well and two ships. The investment cost of the test well that has already been drilled, and will be reused for the most part, was estimated at MNOK 535 (2019-kroners) and is not included above.		

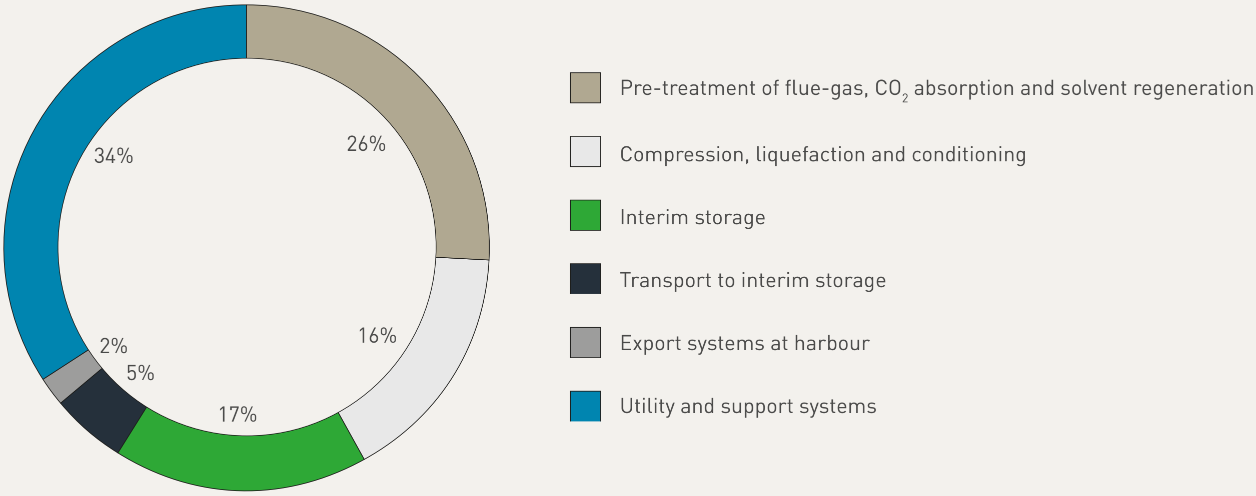


Figure 8: Estimated investment cost spread across the various building blocks in the capture plants, typical values from Fortum Oslo Varme and Norcem.

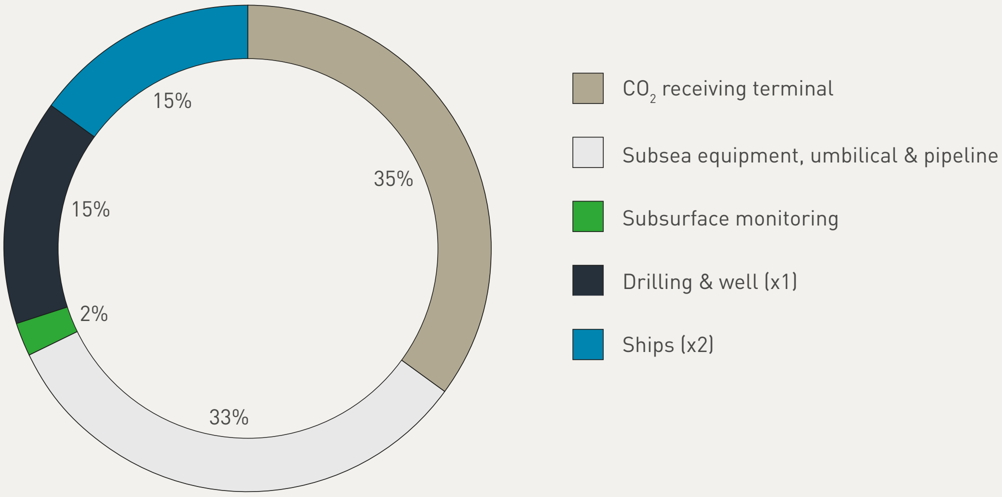


Figure 9: Estimated investment cost spread across the physical elements of the transport and storage facilities.

Other key learnings related to the project development

Some of the learnings aggregated during the development of Longship are related to more specific topics than those presented in the previous pages. Four such key learning points are presented below.

Key learning points

- It is possible to design liquid CO_2 transport ships as typical LPG-type carriers ("fully pressurized" liquefied gas carriers), with a few adjustments. The ship design developed for the project has a cargo capacity of up to 7,500 m^3 (for liquid CO_2 at approximately 15 barg). This will allow competitive bids when using existing shipbuilding markets.

- The HSE activities and practices used in typical industrial projects have been well suited for this kind of project (HAZID, HAZOP, ENVID, BAT, etc.). No significant challenges specific to CO_2 have been identified. However, the particular properties of CO_2 will require special attention, e.g. that it is heavier than air and therefore will fall to the ground and may accumulate at low points.

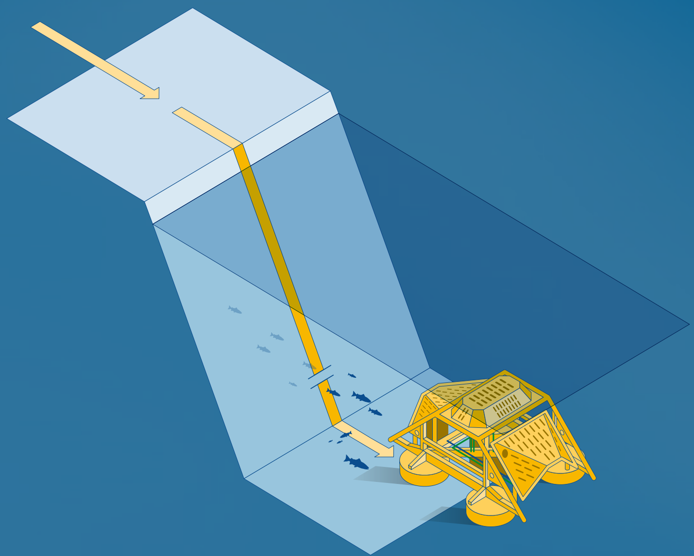
- Issues related to the specific properties of CO_2 should be addressed early in the concept selection phase and be kept in mind through the subsequent design phases. They will typically impact material selection, zone classification, flow assurance, release and dispersion behaviour, etc. For industries that are used to handling hydrocarbons it may be an added challenge to simplify design to take advantage of the fact that CO_2 is not flammable.

- It is feasible to use tanker trucks as part of a CCS chain to connect a capture site with its export terminal (or hub). The distance by road between Klemetsrud and the Port of Oslo is 14 km and truck transport is preferred over a pipeline by Fortum Oslo Varme. A solution with trucks has fewer risks related to zoning processes and geological conditions, although the operating costs will increase rapidly with distance. At least three different potential suppliers for the transport service have been identified by Fortum Oslo Varme, showing that this service is commercially available.

03

TECHNOLOGY QUALIFICATION

The technical solutions to be used throughout the CCS chain are generally well known. However, technology used to capture CO_2 from exhaust gas from combustion or industrial processes is still relatively immature and there are few references to operating facilities of significant size. It has been critical to verify that emissions of potentially carcinogenic substances deriving from the amine solvents used for the capture will be below the allowable limits established by the authorities in Norway. Use of recognized standards for technology qualification has proved useful.



Methodology

The purpose of conducting a technology qualification is to reduce the risk of implementing technology and evaluate the consequences of underperformance, in a structured manner. This is particularly relevant when the technology is new to the buyer and has few, unknown, or irrelevant reference cases. The qualification should be finalized before the FID in a way that reduces the residual risks to levels that the project owner and end-user consider to be acceptable.

In performing technology qualification, it is advisable to use a recognized standard or practice. This will ensure that all relevant aspects are covered and that the results are displayed in a structured and transparent manner suitable for any independent third-party evaluation.

> Through the concept selection and definition phases, Gassnova has required the industrial partners to qualify new or unproven technology elements in accordance with recommended practices from DNV GL, specifically DNV-RP-A203 and DNV-RP-J201.

A systematic approach to evaluating the novelty of the different technology elements in the project is a good starting point for identifying the need for and extent of technology qualification; see Table 3 for an example from DNV-RP-203 (2013).

As indicated in the table, unless a technology is considered proven and well known within the current application area (Category 1 - green colour), there is a need for technology qualification.

Table 3: Technology Novelty Categorization, from DNV-RP-A203 (2013), Table 7-1.
Category 1 indicates that there are no new technical uncertainties, while category 2 to 4 indicates that there are new technical uncertainties or challenges. Colours added by Gassnova.

	Degree of novelty of technology		
Application Area	Proven	Limited Field History	New or unproven
Known	1	2	3
Limited knowledge	2	3	4
New	3	4	4

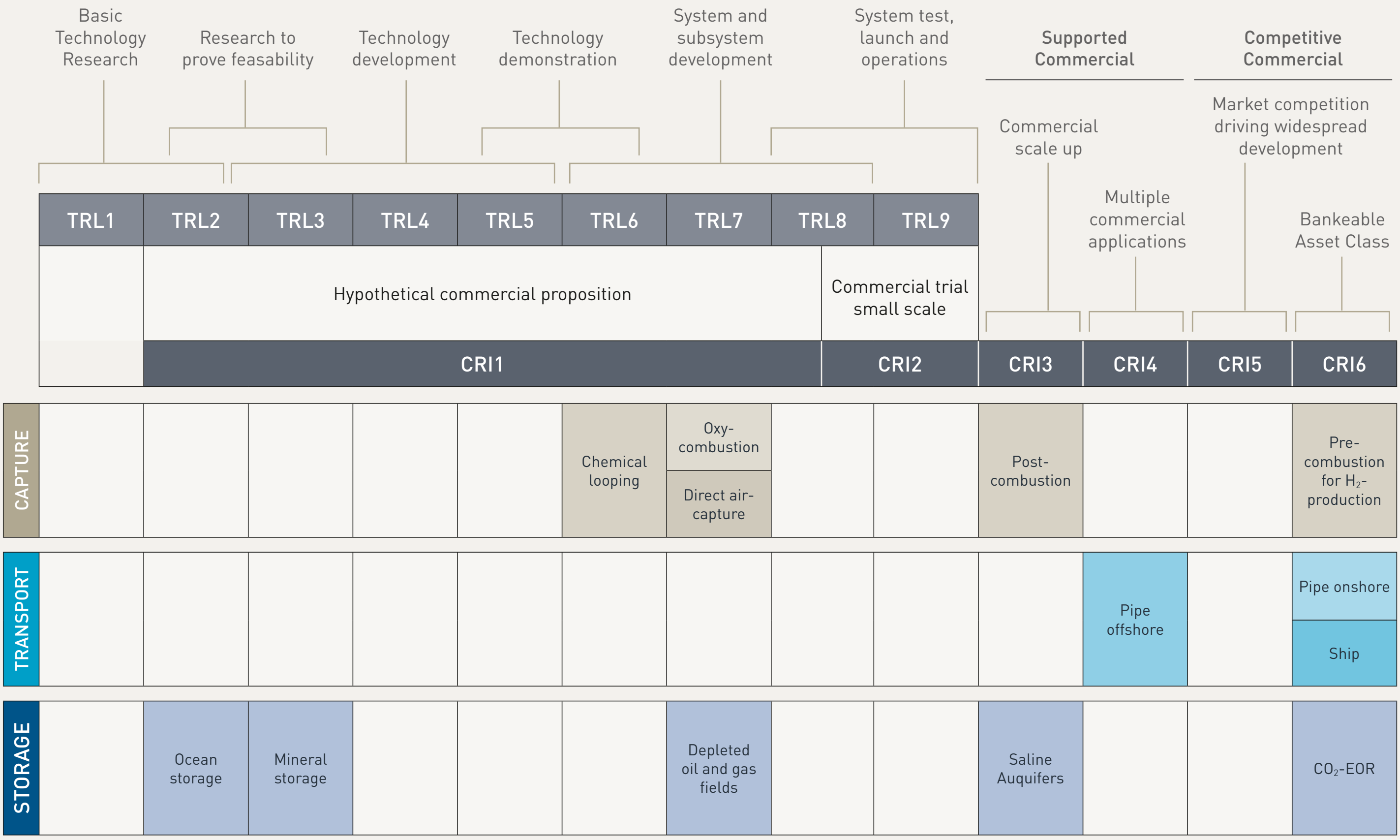


Figure 10: Evaluation of the maturity of CCS technology elements. From "Potential for reduced costs for carbon capture, transport and storage value chains (CCS)", DNV GL, 2019. Report No.: 2019-1092, Rev. 2

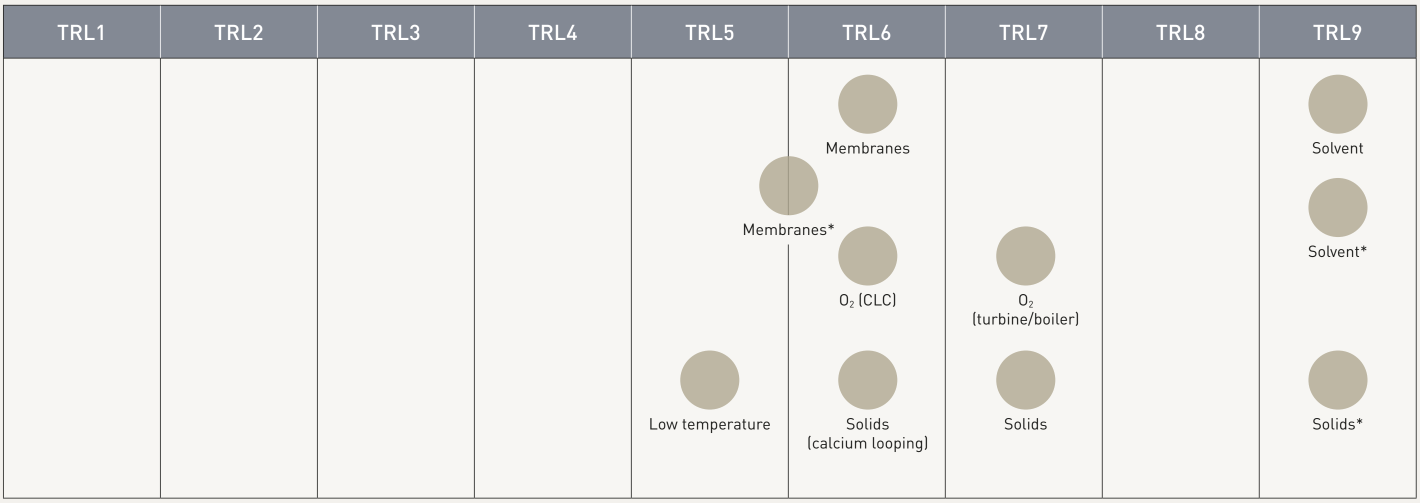


Figure 11: Technology readiness level for different CO_2 capture technologies. Technologies used for hydrogen production at pressurized conditions are denoted with *. From "Technology status for CO_2 capture, transport and storage", Gassnova, 2019.

> Using an independent third party to perform or to verify the technology qualification may be an efficient way to define and execute an unbiased qualification program.

Figure 10 shows the maturity of various technology elements relevant to CCS in terms of Technology Readiness Level (TRL) and Commercial Readiness Index (CRI), as evaluated by DNV GL in a study for Gassnova. The TRL is a measure used to rank different technologies according to their history of demonstration and qualification, while the CRI is a complement to TRL to assess commercial maturity.

The transport part of the CCS chain is considered to be the most mature. For the storage part the maturity levels are very dependent on the storage type/site. For capture technology, the maturity varies a lot depending on both the type of technology and the application, as further shown in Figure 11.

Technology qualification should be risk based and build on the precautionary principle. Key elements are typically:

- Strategy for technical fall-back options
- Technology vendor alternatives
- Evaluate QA system at vendor
- Third-party assessment of available documentation
- Mapping in-house competence (on the buyer side)
- Evaluate reference cases: recent, reliable, relevant; duration and size
- Identify areas where the intended application represents a step-out from previous experience/references
- Plan and perform pilot testing, if needed
- Assess availability tools and methods needed for the qualification, e.g. related to HSE properties of solvents

Key learning points

- Use of recognized standards for technology qualification has proved extremely useful. It has helped companies that have less experience with technology qualification to work systematically with new technology. A common structure and methodology also made the technology qualification by Norcem and Fortum Oslo Varme more transparent, which made it easier for Gassnova to evaluate their deliverables from the concept and FEED studies.
- TRL is often assigned based on the least mature part of the technology, which makes the readiness level alone unsuitable as a measure for how much work is needed to qualify the technology. Developing a technology qualification program will identify the time and resources needed to qualify a technology.
- Both Norcem and FOV used DNV GL as an independent third party to verify their technology qualifications. Upon completed verification DNV GL issued "Statement of qualified technology" for the different technologies that were qualified. The involvement of such a third party aided the technical discussions between Gassnova, the industrial partners, and the technology providers.

Technology qualification in Longship

Throughout the project development, Gassnova has maintained the position to encourage use of proven technology, unless the benefit of using new technology elements significantly outweighs the risks.

For the transport and storage part of the project, Northern Lights intends to utilize standard and proven technology used in the CO_2 industry. Only minor uncertainties have been identified during the technology maturity mapping process in the FEED phase.

For the capture part of the project, both Fortum Oslo Varme and Norcem will use technologies that are unproven in the intended applications; first and foremost they have executed qualification programs for their respective amine technologies, but Norcem has also qualified a CO_2 compressor with heat recovery and waste heat recovery units (WHRU).

> For both companies, it has been important to verify and document that their selected capture technologies will allow them to operate within Norwegian emissions regulations.

Amine capture technology is based on a chemical reaction between the amine solvent and the CO_2 in the flue gas. Central questions regarding the use of this kind of technology are related to how much CO_2 will be absorbed in the amine, how aerosol content in the flue gas will affect carry-over and emission of amines, which chemical species the amine may degrade into, how fast the degradation occurs, etc.

In the planning of the now cancelled Norwegian full-scale CO_2 capture project at Mongstad (CCM), emissions to air of possibly carcinogenic substances related to amines were flagged as a potential showstopper. In 2008, a comprehensive research programme was initiated to identify and close knowledge gaps with respect to the formation of potential carcinogenic substances and the toxicity level of these substances, known as nitrosamines and nitramines. The work resulted in the development of rigorous methods to evaluate these effects. Several amine technology vendors and projects, including the two capture projects in Longship, have used these methods to evaluate their technology*.

After completing their concept study in 2018, Fortum Oslo Varme selected the Shell amine capture technology. This technology has a reference plant in the Boundary Dam facility in Canada, operated by Sask Power. The Boundary Dam flue gas differs from the flue gas found at Fortum Oslo Varme's waste-to-energy plant and it is also operated under less strict emission requirements than will be the case in Norway. To verify amine emission level, solvent degradation and energy efficiency, Fortum Oslo Varme designed, installed and operated a custom-made pilot plant for the Shell capture technology (DC-103 solvent). Based on the test results from the pilot, the technology was deemed qualified for use at the operating conditions and flue gas composition expected at the waste-to-energy plant.

Norcem screened various capture technologies before selecting the amine-based technology from Aker Solutions (now Aker Carbon Capture) before starting the feasibility study late 2015. The technology had already been qualified for the CCM project at Mongstad, partly through testing at TCM. However, to establish the actual capture performance and expected amine emission levels with the flue gas in Brevik, Norcem required a pilot test at their cement plant. The early phase of Norcem's technology qualification programme was funded by the CLIMIT programme, including a test campaign performed by Aker Solution using their Mobile Test Unit (MTU) and covering some 7,400 operating hours.

Key learning points

- It has been possible to develop the CCS chain with limited use of new technology, and only the amine technologies used for capture of CO_2 have had no fallback options.
- Reference cases used as "evidence" in technology qualification must be scrutinized to assure relevance. According to DNV-RP-A203, *"Only knowledge and experience that is documented, traceable and accessible to the qualification team should be used"*. This understanding has been at the heart of the capture technology qualification done by both Norcem and Fortum Oslo Varme, where it has been crucial to verify the amine degradation and emissions to air.
- The experience with qualification of amine technology during the CCM project has been valuable in the development of Longship. Fortum Oslo Varme, Norcem and Yara, as well as their technology providers and engineering companies, have used the tools, methods and expertise developed around the CCM project in their processes to select and qualify capture technology.

* More info on the "tool-box" and qualification methods developed for the CCM-project can be found at ccsnorway.com/hse-studies/

Images
Technology Centre Mongstad (TCM): p. 2–3, 24–25, 47 **Fortum Oslo Varme:** p. 37 **Styrk Fjørtoft:** p. 40
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