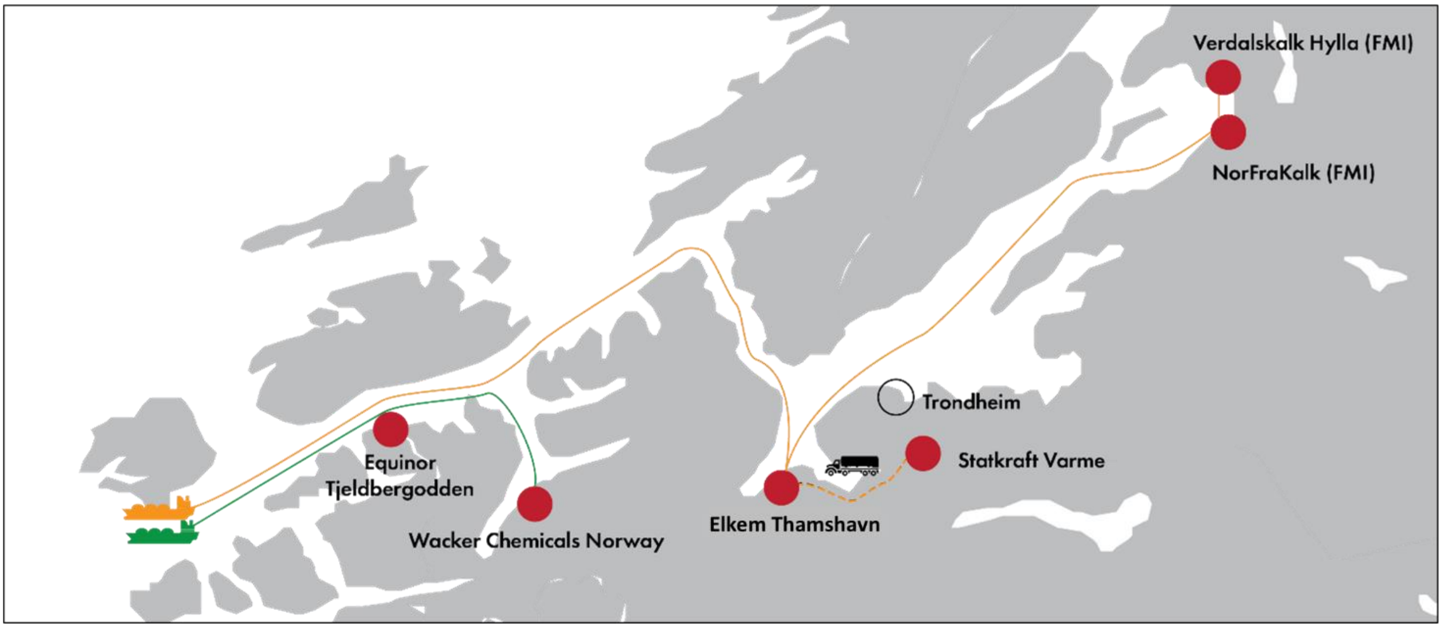

Report

The CCS Midt-Norge cluster

Industrial CCS collaboration for exploring synergies and common interests

Authors:

Kristin Jordal, Øyvind Langørgen, Donghoi Kim, Francesco Finotti, Simon Roussanaly, Nicola Marsh, Mari Voldsund

Report No:

2023:00230

Clients:

Statkraft Varme, NorFraKalk, Verdalskalk Hylla, Elkem Thamshavn, Wacker Chemicals Norway Holla Metall, Equinor Tjeldbergodden Methanol Plant, Gassnova

SINTEF Energy Research
Postal address:
Postboks 4761 Torgarden
7465 Trondheim, Norway

Switchboard: +47 45456000

energy.research@sintef.no

Enterprise /VAT No:
NO 939 350 675 MVA

Report

The CCS Midt-Norge cluster

Industrial CCS collaboration for exploring synergies and common interests

KEYWORDS
CCS, CO2 transport, CO2 logistics, CCS clusters, CCS financial and regulatory framework

VERSION
1.0

DATE
2023-03-27

AUTHORS
Kristin Jordal, Øyvind Langørgen, Donghoi Kim, Francesco Finotti, Simon Roussanaly, Nicola Marsh, Mari Voldsund

CLIENTS
Statkraft Varme, NorFraKalk, Verdalskalk Hylla, Elkem Thamshavn, Wacker Chemicals Norway Holla Metall, Equinor Tjeldbergodden Methanol Plant, Gassnova

CLIENTS' REFERENCES
Svein Bekken (Gassnova), Bjørn Hølaas (Statkraft Varme)

PROJECT NO.
502003040

NO. OF PAGES
41

SUMMARY

The CCS Midt-Norge project phase 1 has been a collaboration between Franzefoss Minerals, Statkraft Varme, Elkem Thamshavn, Wacker Holla Metall, Equinor Tjelbergodden and SINTEF. CO_2 emissions from the industries in the project are around 1.5 Mt/year. Power consumption for capturing and liquefying 90% of this CO_2 for ship transport is estimated at around 30 MW_e (220 GWh annual electric energy consumption). Several logistics cases were investigated for transporting captured CO_2 to e.g., the Northern Ligths storage facility. It has been verified that there are cost benefits if transport infrastructure (intermediate storage tanks, ships) is shared. Other common interests for the cluster include legal and regulatory drivers for CCS implementation, such as the EU ETS and carbon removal certification. Continued cluster cooperation towards a preferred joint concept for CO_2 transport and storage is envisaged.

PREPARED BY
Kristin Jordal

SIGNATURE
Kristin Jordal
Kristin Jordal (30. mar. 2023 12:40 GMT+2)

CHECKED BY
Rune Aarlien

SIGNATURE

APPROVED BY
Mona J. Mølnvik

SIGNATURE
Mona J. Mølnvik
Mona J. Mølnvik (30. mar. 2023 21:03 GMT+2)

REPORT NO.
2023:00230

ISBN
978-82-14-07964-7

CLASSIFICATION
Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
Draft	2023-01-31	First draft to CCS Midt-Norge partners and Gassnova
Draft v2	2023-02-27	Second draft to CCS Midt-Norge partners and Gassnova
Draft v3	2023-03-13	Third draft to CCS Midt-Norge partners and Gassnova
Draft v4	2023-03-16	Fourth draft to Equinor and Statkraft for final clarifications
V1.0	2023-03-27	First version of report released

Table of contents

1 Introduction – about the CCS Midt-Norge project

The Norwegian climate goals are to reduce climate gas emissions with 50-55% by 2030 and with 90-95% by 2050, compared to emissions in 1990[1]. CO_2 Capture and Storage (CCS) is a set of technologies for CO_2 capture, conditioning, transport, injection, and geological storage, that can be an enabler of drastic reductions of CO_2 emissions. The Norwegian full-scale CCS project Longship[2] is an important pioneering project in this area, and many others need to follow.

CCS is however costly to implement for the industries that need to cut costs to contribute to fulfilling Norway's climate goals. The **CCS Midt-Norge project** was therefore established, to do a first verification of the assumption that the cost for transporting captured CO_2 to storage can be reduced if industries in Mid-Norway (Trøndelag and Nord-Møre area) cooperate.

This report is the final outcome of the CCS Midt-Norge project, which was executed from March 2021 until February 2023. The purpose of the project has been to establish a regional cluster for CCS infrastructure in Mid-Norway. The industries cooperating in the project are Franzefoss Minerals (representing Verdalskalk Hylla and NorFraKalk), Statkraft Varme Heimdal, Elkem Thamshavn, Wacker Holla Metall and Equinor Tjeldbergodden. Statkraft Varme has been project owner and SINTEF has been project manager and main executor of the work.

The project has mapped prerequisites for the individual industry actors in the cluster to deliver CO_2 to a common infrastructure and investigated the cost of different logistics options for CO_2 transport by ship to the CO_2 receival and storage facility of Northern Lights, close to Bergen. Northern Lights is the CO_2 transport and storage operator in the Longship project. The CCS Midt-Norge cluster members have discussed the potential and obstacles for building business models for CCS and identified common points of interest that need to be further addressed. A tentative roadmap for CCS deployment in the region has been established.

The project has not focused on CO_2 capture integration at the different industrial sites – the development of CO_2 capture activities has been going on in parallel for each of the partners and is only mentioned briefly. However, the envisaged CO_2 capture technologies for each site, as well as the climate plans for the industries in the cluster are an important part of the context for this study. In brief, the climate plans for the industries state that

- The goal of the Franzefoss Minerals Group is to achieve carbon neutral quick lime production before 2050. This goal encompasses both NorFraKalk and Verdalskalk.
- Statkraft Varme's goal is to be carbon neutral by 2040. Several measures have been taken, including a feasibility study on CCS.
- Elkem's goal is to increase the use of biocarbon to 40% in their Norwegian smelters by 2030, and ultimately to achieve carbon-neutral production of silicon and ferrosilicon. The overall Elkem goal is net zero emissions by 2050.
- Wacker Group has set ambitious sustainability targets, aiming for CO_2 neutral silicon production by 2030.
- Equinor has an overall goal of net zero emissions before 2050.

The project has partly been funded by the industry partners and partly by Gassnova through the CLIMIT Demo Programme, project number 620162.

---

[1] Klimaendringer og norsk klimapolitikk - regjeringen.no

[2] CCS Norway - Sharing knowledge from the Norwegian CCS project Longship

2 The industries in the CCS Midt-Norge project

The six industry sites involved in the CCS Midt-Norge project are:

- NorFraKalk, lime production plant (part of Franzefoss Minerals, FMI)
- Verdalskalk Hylla, lime production plant (part of Franzefoss Minerals, FMI)
- Statkraft Varme Heimdal, waste-to-energy plant for district heating in Trondheim
- Elkem Thamshavn, silicon and microsilica production plant
- Wacker Chemicals Norway - Holla Metall, silicon and microsilica production plant
- Equinor Tjeldbergodden, methanol production plant

They are shown on the map in Figure 2-1, with their CO_2 emissions indicated by the circle sizes. Together they have yearly CO_2 emissions of about 1.5 million tonnes. This is 3% of the total Norwegian greenhouse gas emissions for 2021.

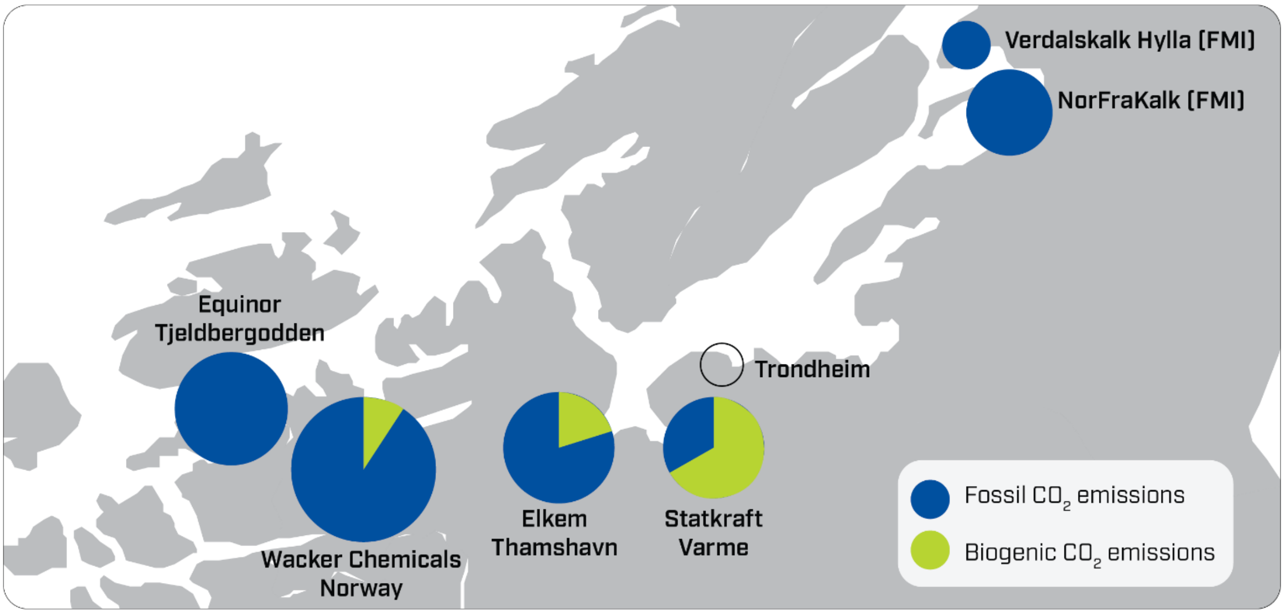

Figure 2-1 Industries involved in the CCS Midt-Norge project.

The yearly CO_2 emissions for each plant is shown in Table 2-1. There is a large span in CO_2 amount between the plants, how the CO_2 is generated, and the CO_2 concentration and level of impurities in the flue gas. There are also large differences in the amount of heat available on-site. All these parameters will affect the choice of capture technology and the extent of CO_2 cleaning needed to produce a sufficiently pure CO_2 stream. When the CO_2 stream is purified to the required level, the further transport and logistics infrastructure, which is the main scope of this study, is mainly governed by the amount of CO_2 captured from each plant.

Table 2-1 Yearly CO_2 emissions (tonnes/year) based on recent data for each plant.

Verdalskalk	NorFraKalk	Statkraft Varme Heimdal	Elkem Thamshavn	Wacker Holla Metall	Equinor Tjeldberg-odden	SUM
55 000	174 000	240 000	290 000	492 000	260 000	1 511 000

CO_2 capture requires energy. Commercially available capture technologies (amines) will mainly need substantial amounts of heat for amine regeneration. However, power requirements will also increase, largely due to CO_2 liquefaction. There are also capture technologies (e.g., membranes and pressure-swing adsorption) that mainly use electric power, rather than heat for capture, and where the power consumption per tonne of captured and liquefied CO_2 will be higher than when amines are used. Lack of power capacity to the site is a possible challenge for some of the plants involved in the project.

In the following sub-chapters, a short description is given for each plant, providing information about their process, energy system, CO_2 emissions, plans for CO_2 capture, and estimated amount of captured CO_2. Indicative power requirements and estimated annual energy consumption for CO_2 capture, compression and liquefaction are also given. Power and energy consumption are calculated based on information from the plants, data from literature for amine capture technology, and compression and liquefaction power are calculated assuming a pure CO_2 stream. This is described in Section 2.8.

Norske Skog paper mill at Skogn is not a part of the CCS Midt-Norge project but there has been some discussions and information exchange during the CCS Midt-Norge project. Norske Skog Skogn has CO_2 emissions of about 230 000 tonnes/year, of which around 98% is from biogenic sources. Possible inclusion of Norske Skog Skogn at a later stage would be welcome. It will increase the amount of CO_2 being captured and stored from the region, as well as being beneficial to all partners by possibly reducing transport and logistics costs per tonne of CO_2.

2.1 NorFraKalk

NorFraKalk manufactures and sells quick lime (CaO), as well as related limestone products from its own facility at the Ørin industrial area in Verdal. NorFraKalk was founded in 2004 by the Norwegian company Franzefoss Minerals AS (50%) and the Finnish company Nordkalk Oy Ab (50%). The main product is high-quality quick lime for the Northern European market, where it is used to produce precipitated calcium carbonate (PCC). PCC is further used as filler and coating in the paper industry, in polymer production, in production of health and medical tablets, etc.

NorFraKalk produces on average about 170 000 tonnes per year of lime in a modern and advanced plant with 19 employees. The feedstock is 340 000 tonnes per year of limestone from the Tromsdalen opencast mine, about 20 km away from the plant.

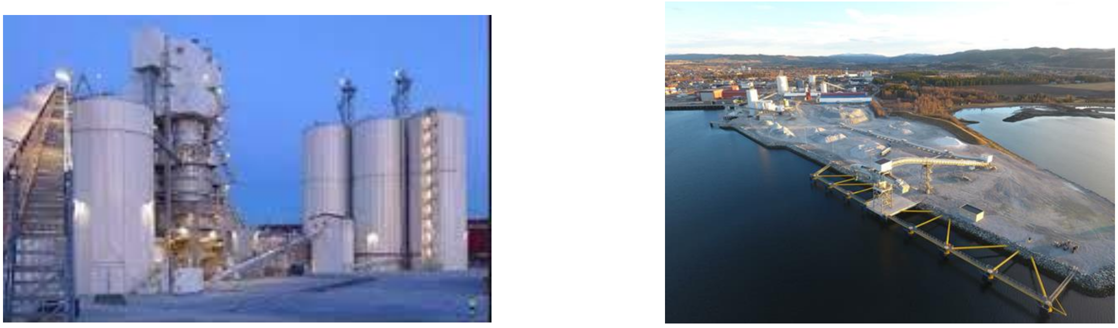

Figure 2-2 NorFraKalk and new quay.

The quick lime is produced in a 45-meter tall twin-shaft parallel lime kiln. Both shafts are fed continuously from the top with limestone in sizes between 30 and 100 mm. The feed uses 28-30 hours to the bottom where it is poured out as quick lime. Both shafts have several oil lances inserted from the top as shown in Figure 2-3. The two shafts are operating in an alternating mode.

In the figure, shaft 1 is in burning mode to achieve high enough temperatures for calcination. The hot exhaust gas passes over to shaft 2 through the crossover channel and is used to heat the limestone feed in shaft 2. After about 13 minutes, the cycle switches so that shaft 2 is in burning mode while shaft 1 is using the heat from the exhaust gas. In the bottom part, both shafts have air injection from the bottom to cool the final product.

This direct contact between limestone feed and hot gases ensures a highly energy efficient process, where the outflowing exhaust gas is just about 100°C. The direct contact with limestone also contributes to some purification of the exhaust gas. The kilns are fired with waste oil. This is cheap and it does also serve as incineration of hazardous waste. About 168 GWh of waste oil is fired per year. Of this, more than 80%, about 140 GWh, remains in the lime product as chemical energy. The plant uses about 7.7 GWh of electric power per year, mainly for compressors and air fans providing the necessary gas flows through the kilns.

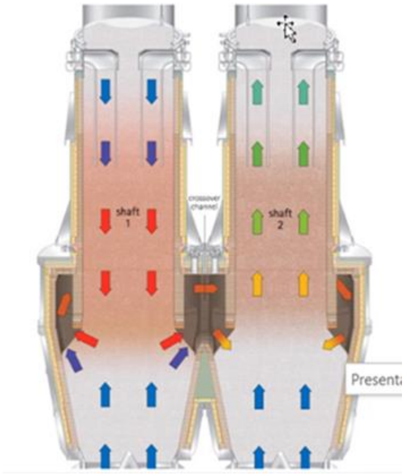

Figure 2-3 Principle of twin-shaft parallel lime kiln.

The CO_2 emissions are about 174 000 tonnes per year. Of this, more than 70% is CO_2 being released from the limestone in the calcination process. The remaining share comes from the oil firing. All the emissions leave through the same stack. With an estimated CO_2 capture rate of 90%, 156 600 tonnes of CO_2 will be captured on average over the whole year. However, the dimensioning capacity for the capture plant and the needed CO_2 infrastructure should be higher and is better evaluated using daily values, considering periods of maintenance stops and periods of lower or higher production. NorFraKalk may have large variations in production from week to week. This is reflected in the daily values given in Table 2-2.

NorFraKalk has been involved in an earlier CO_2 capture project, looking at possible CO_2 capture technologies. The low amount of available heat makes it difficult to choose an amine-based capture plant. Such a plant will need a lot of heat at about 130-140°C for amine regeneration. Instead, a membrane solution for CO_2 separation is being evaluated. It will give a capture rate of 90% and require only electric power. The estimated electric power requirement for the membrane capture and CO_2 compression and liquefaction is 366 kWh/tonne CO_2 captured, equivalent to 9.2 MW electric power when using the daily dimensioning value provided in Table 2-2. It will give an extra electric energy consumption of 57.3 GWh per year using the yearly value for CO_2 captured. I.e., nearly 7.5 times more than today's consumption of 7.7 GWh. It needs to be verified that the local and regional power grid and transforming stations can handle this added power.

The CO_2 concentration in the exhaust gas is about 23 - 25 vol%. This is beneficial since it gives a high driving potential for the capture process. The exhaust gas contains other components and impurities, but the level is generally low, well below emission permits. This is also the case for dust, which can be a problem for membrane separation. The plant has a bag filter system and the dust level downstream the filter is normally about 2-3 mg/Nm^3, which is much lower than the permit of 15 mg/Nm^3. Still, a possible capture plant vendor must confirm whether this is acceptable, or if additional dust removal will be needed.

Table 2-2 Dimensioning values for CO_2 generated and CO_2 captured at NorFraKalk.

		CO_2 generated	Capture rate	CO_2 captured
Yearly value (*)	tonnes/year	174 000	90 %	156 600
Daily value (**)	tonnes/day	670	90 %	603

(*) This is the amount of CO_2 generated and captured from the plant on average over a whole year. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture, compression, and liquefaction.
(**) CO_2 emissions that can appear for periods of several days up to 3-4 weeks, due to periods of increased production. Based on max capacity of kiln, which is 650 tonnes per day of quick lime. This value is used further in the study as dimensioning capacity for the CO_2 capture, infrastructure, and transport chain, and for calculating required power (in MW) for CO_2 capture, compression, and liquefaction.

There is some available space that can be used for a capture plant including CO_2 processing (purification, compression, liquefaction) and intermediate storage. Two areas of 1100 and 2000 m^2 have been marked as the most likely location alternatives. An on-site intermediate storage for some days will be needed. From this storage, the CO_2 will most likely be transported with ship. The quay capacity is good, especially with the new quay shown in Figure 2-2.

When the quick lime from NorFraKalk is used to produce PCC at the customer's plants in Europe, it will need a lot of CO_2 to form pure carbonate. As much as 95-98% of the CO_2 amount released when producing the quick lime, will be bound in the PCC. PCC is part of the CO_2 emissions trading system (ETS). However, it is awarded only if the PCC is produced the same place where the CO_2 from the quick lime production is emitted. The lime industry is working to get acceptance within ETS that these two productions can be at different places and in different countries. This would considerably improve the business case for CO_2 capture at NorFraKalk.

2.2 Verdalskalk Hylla

Verdalskalk Hylla produces quick lime and hydrated lime which is delivered mainly to Norwegian customers. Most of it is used for cleaning flue gas emissions to air, sewage cleaning, and for water purification. The lime kiln has a capacity of 65 000 tonnes quick lime per year, but the average production is about 53 000 tonnes/year. About 16 000 tonnes/year of the quick lime is further processed to hydrated lime, giving about 20 000 tonnes per year. Verdalskalk Hylla started lime production already in 1897. Today it is part of Franzefoss Minerals and partly owned also by the Danish Faxe Kalk and Finnish Nordkalk Oy Ab. The plant is operating on a five-shift basis with 15 employees.

Figure 2-4 Verdalskalk Hylla.

The feedstock is 90 000 tonnes/year of limestone from the Tromsdalen opencast mine, about 28 km from the Hylla plant. This mine is owned by Verdalskalk and is one of Europe's largest limestone deposits, providing limestone with high purity and whiteness, making it especially suitable for paper pigments. It also delivers limestone to NorFraKalk.

The production process is generally the same as at NorFraKalk as described in Section 2.1. However, the Hylla kiln is smaller, with 25 meters height, and it is also older and with less energy recovery. Some of the quick lime produced in the kiln is further processed to hydrated lime by adding some water to the quick lime. About 55 GWh of waste oil is fired in the kiln per year, of which about 80% remains in the lime as chemical energy. The plant uses about 5.7 GWh of electric power per year, mainly for compressors and air blowers.

The CO_2 emissions from Verdalskalk Hylla is on average about 55 000 tonnes per year, where all of it comes from the kiln. The hydration process does not produce any CO_2. Most of the CO_2 emissions, about 70%, comes from the limestone when it is burnt (calcined) in the kiln. The rest comes from the waste oil firing. With 90% CO_2 capture rate, the yearly amount of captured CO_2 will be 49 500 tonnes/year. Due to possible large variations in production volume in just few days, the yearly amount cannot be used as dimensioning capacity for the capture plant and transport and logistics infrastructure. A higher daily value is used for this purpose, as shown in Table 2-3.

Verdalskalk Hylla has not participated in any studies evaluating possible capture technologies for the plant. Due to the very low amount of available heat needed for an amine capture plant, it will be relevant to use the same membrane separation technology as investigated by NorFraKalk. It will give 90% capture rate and require only electric power and no heat. The CO_2 concentration in the flue gas from the kiln is normally just above 20 vol%, a relatively high value and beneficial for a CO_2 capture process. There is a lot of dust from the process, but this is reduced to low levels in a bag filter system before the gas is emitted to the surrounding air. However, operating a membrane for CO_2 capture may possibly put very stringent conditions on the gas to be treated. A membrane system vendor must confirm whether the gas is acceptable, or if additional cleaning is needed.

With the CO_2 concentration being a little lower than for NorFraKalk, the specific energy requirement for CO_2 capture will be slightly higher. It is estimated to be 417 kWh/tonne CO_2 captured, compressed, and liquefied (compared to 366 kWh/tonne for NorFraKalk). The additional electric power required will then be 3.0 MW when using the dimensioning daily value provided in Table 2-3. It will give an extra electric energy consumption of 20.6 GWh per year, more than 3.5 times than today consumption of 5.7 GWh. It needs to be verified that the local and regional power grid and transforming stations can handle this added power.

Table 2-3 Dimensioning values for CO_2 generated and CO_2 captured at Verdalskalk Hylla.

		CO_2 generated	Capture rate	CO_2 captured
Yearly value (*)	tonnes/year	55 000	90 %	49 500
Daily value (**)	tonnes/day	192	90 %	173

(*) This is the amount of CO_2 generated and captured from the plant in average over a whole year. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture, compression, and liquefaction.
(**) CO_2-emissions that can appear for periods of several days up to 3-4 weeks, due to periods of increased production. Based on max capacity of kiln, which is 65 000 tonnes of quick lime per year, and operational time of 8400 hours per year. This value is used further in the study as dimensioning capacity for the CO_2 capture, infrastructure, and transport chain, and for calculating required power (in MW) for CO_2 capture, compression, and liquefaction.

It is at present very limited available space at the plant. However, Verdalskalk owns an area of about 7000 m^2 besides the plant which can be used. It will need blasting and construction work to make this area suitable for the CO_2 capture plant, including compression, liquefaction, and intermediate storage. There is a small quay at Verdalskalk Hylla, but the limited size and depth makes it unsuitable, and it is not being used. All transport of limestone, produced lime, and waste oil is by trucks. In total 12 – 14 trucks are driving to and from the plant each day, on a smaller road of 1.5 km through a residential area. Truck transport of CO_2 will need additionally 4 – 5 trucks per day with the captured values in Table 2-3 and truck capacity of 35 tonnes of CO_2 which is a likely value also being used by other capture studies in Norway.

A possible solution is to transport the CO_2 to an intermediate storage at NorFraKalk, from where it can be shipped. The road distance is 11 km. It could also be a possibility to transport the CO_2 in a pipe at the seabed from Hylla to NorFraKalk, but this is probably difficult and expensive due to the seabed conditions. Upgrading the quay could be a more feasible solution, at least to allow smaller ships that can work as both on-site storage volume and as shuttle ship/barge, transporting the CO_2 to a larger storage.

There is at present not an actual business case for CO_2 capture at Verdalskalk Hylla. However, as for NorFraKalk, the lime will bind a lot of CO_2 when being used by the customers, as much as 95-98% of the CO_2 amount released when producing the lime. If it will be accepted within the CO_2 emissions trading system (ETS) that the lime production with CO_2 emissions, and the lime use with CO_2 uptake, can be at different places and in different countries, it would considerably improve the business case for CO_2 capture at Verdalskalk Hylla.

2.3 Statkraft Varme Heimdal /Heimdal Varmesentral (HVS)

Heimdal Varmesentral is part of Statkraft Varme, which is the business unit within Statkraft being responsible for the district heating activities in Trondheim. Heimdal Varmesentral (HVS) is a waste-to-energy (WtE) plant incinerating residual waste that cannot be recycled or used in other ways, converting the waste to useful heat. Waste is received from the whole Mid-Norway region. About 220 000 tonnes of waste is incinerated per year. The heat is distributed to the Trondheim community through a 250 km long district heating pipe network. HVS has been in operation since 1986 and today it covers about 30% of Trondheim's heat demand. Statkraft Varme has about 125 employees, of which about 100 are located in Trondheim.

Figure 2-5 Statkraft Varme, Heimdal Varmesentral.

HVS has three incinerators with a total heat capacity of 80 MW. Line 1 and 2 from 1986 with a joint capacity of 33 MW, and line 3 from 2007 with 47 MW capacity. About 500 GWh (500 million kWh) of heat is delivered each year from the plant. The heat demand varies a lot over the year. In summertime there will be excess heat which is removed by air coolers placed on the roof of the plant. This can amount to as much as 40-50 MW and about 80-120 GWh per year. Statkraft Varme also delivers district cooling based on absorption coolers which need heat for operation. This heat demand, together with other new heat deliveries, will reduce the amount of heat being dumped to the surroundings by the air coolers.

An overview of the process is shown in Figure 2-6. Waste is fed from the receiving bunker into an angled moving grate where it is combusted with air. The hot flue gas goes up the furnace and into the heat exchanger system where the heat is extracted. The flue gas then passes through the cleaning systems to remove components such as NOx, SOx, and dioxins, and a large bag filter to remove particulates, before being emitted through the stack.

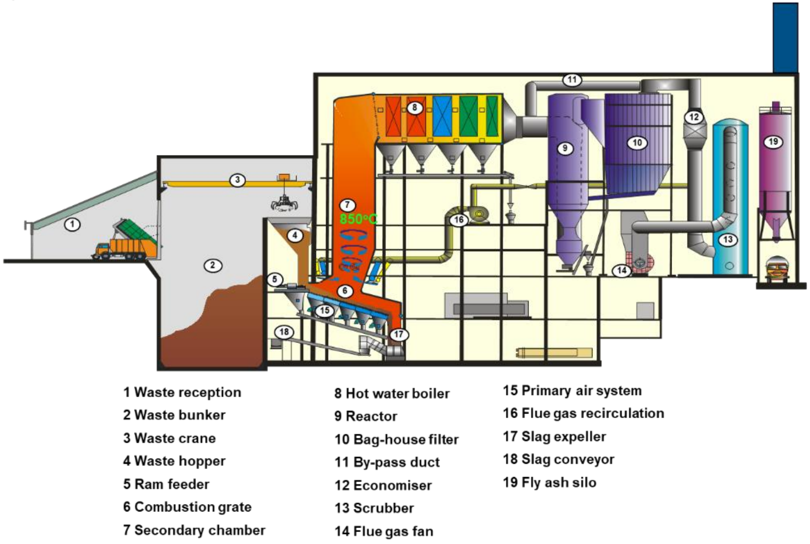

Figure 2-6 Overview of the waste-to-energy process at Heimdal Varmesentral.

The flue gas from waste combustion is the source of CO_2 being emitted from the plant. About 1.1 tonne of CO_2 is generated per tonne of waste. With 220 000 tonnes waste per year, the amount of CO_2 generated will in total be about 240 000 tonnes per year. The CO_2 concentration in the flue gas is about 11.0 vol-%. There will be some variation in CO_2 generation because of variation in amount of waste being incinerated, variation in waste quality and carbon contents, and maintenance stops. They are arranged so that at least one line is always in operation. With all three lines in operation, about 25 – 30 tonnes CO_2 is generated per hour, and in the minimum case with only line 1 or 2 in operation, it will be just 6 tonnes CO_2 per hour. The dimensioning values for CO_2 generation and capture is shown in Table 2-4.

Table 2-4 Dimensioning values for CO_2 generated and captured at Statkraft Varme Heimdal.

		CO_2 generated	Capture rate	CO_2 captured
Yearly value (*)	tonnes/year	240 000	90 %	216 000
Daily value (**)	tonnes/day	658	90 %	592

(*) Based on 220 000 tonnes waste/year, and about 1.1 tonne CO_2 generated per tonne of waste. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture, compression, and liquefaction.
(**) CO_2 generated and captured per day is calculated as an even distribution of the yearly value since the plant is operating continuously with only shorter maintenance stops where at least one line is still in operation. This value is used further in the study as dimensioning capacity for the CO_2 capture, infrastructure, and transport chain, and for calculating required power (in MW) for CO_2 capture, compression, and liquefaction.

Statkraft Varme has an ongoing project evaluating solutions for CO_2 capture at HVS. Capture using amine absorption is the most likely option, which is already a commercially validated solution. The estimated thermal power (heat) requirement is about 27 MW for CO_2 capture. Heat pumps will be used for energy recovery from the CO_2 capture plant and delivery of recovered heat to the district heating network. The electric power requirement for CO_2 capture, compression, liquefaction and heat pumps is estimated to 10 MW_e. This includes roughly 3.5 MW_e for capture, compression and liquefaction and 6.5 MW_e for heat pumps. Space will be required on site for the capture plant, the CO_2 processing units (purification, compression, liquefaction), as well as local CO_2 storage. The storage capacity is based on one day of CO_2 capture. The total footprint of the whole CO_2 plant including storage is estimated to about 5-6000 m^2. There is very limited space available, so there are ongoing discussions with Trondheim Municipality about a possible area for a capture plant.

The plant is not located close to a harbour or railway. The captured CO_2 will most likely have to be transported by trucks to the harbour at Orkanger, where intermediate storage and ship loading facility can be shared with Elkem Thamshavn. The capacity of one truck is maximum 35 tonnes, so 17 truckloads per day will be needed to transport the captured 592 tonnes/day.

About 67% of the CO_2 generated from the waste, is biogenic CO_2. When biogenic CO_2 is captured, it will contribute to carbon dioxide removal (CDR). In most emissions scenarios consistent with climate goals, there will be need for increased CDR capacity. However, in the present EU emission trading system (ETS), capture of biogenic CO_2 is not rewarded. It is expected to be included in some way in the future, through carbon removals certification, thereby contributing positively to a business case for CO_2 capture at Statkraft Varme Heimdal.

2.4 Elkem Thamshavn

Elkem Thamshavn is part of the Elkem ASA group which have operations and production along the whole silicon chain. From quartz to silicon metal and further to downstream specialities, such as ferrosilicon. Elkem has 29 plants and production facilities world-wide, and they are owned by the Chinese company National BlueStar.

Figure 2-7 Elkem Thamshavn

Since 1930, there have been different kinds of smelting plants at Thamshavn. A smelter furnace for ferrosilicon was built in 1964, and a new and larger one was added in 1981. The two furnaces were rebuilt to silicon furnaces in 1998 and 2005. They have an electric power consumption of 25 and 45 MW, in total 70 MW. Elkem Thamshavn is today producing about 50 000 tonnes of silicon metal and 25 000 tonnes of Microsilica® per year in these two furnaces. Silicon is a very important material within electronics, computers, solar cells, and semiconductors, as well as an alloy for other metals, such as aluminium. Microsilica® is an important admixture for concrete. Elkem Thamshavn has about 150 employees.

The main raw material is quartz (SiO_2) which is fed to the furnace together with a carbon source (coal, coke, biocarbon or wood chips) which acts as reduction material. Electric current is supplied through the electrodes. The quartz is converted into liquid silicon that is tapped out of the furnace. The oxygen from the quartz and from the inflowing air reacts with the carbon in the reduction material to form CO_2. This is the source of the CO_2 being emitted from such a smelter plant. Microsilica® is formed as dust in the upper part of the furnace and is separated in the downstream filters.

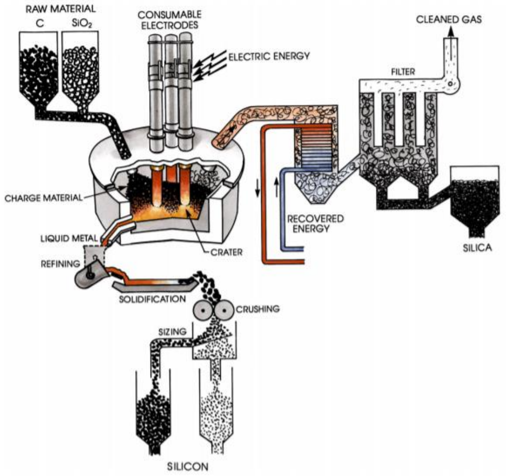

Figure 2-8 Silicon production process. (Schei, Tuset, & Tveit, 1998).

Air is sucked into the furnace, primarily to control the temperature. The off-gas out of the furnaces has a typical average temperature of about 800°C. The gas is cooled down to below 200°C before the filter inlet. The gas cooling is done with an energy recovery system that produces electric power through a steam turbine and supplies heat to district heating. About 180 GWh of thermal energy is recovered in the energy recovery system. The off-gases contain in total a useful thermal power of 60-80 MW. The steam turbine produces on average about 18 MW electric power, covering about 26-28% of the consumption of the furnaces. There is still available heat from the plant, at different temperature levels, that can be used in a CO_2 capture plant.

Elkem has a target to achieve carbon neutral production and CO_2 capture is a main pillar in this work. The most relevant technology for Elkem is amine-based absorption where the amine solvent absorbs the CO_2 from the off-gas in the absorber tower, and where the CO_2 is released from the amine in the stripper tower and will be available as an almost pure CO_2 stream. The CO_2 emissions at Elkem Thamshavn is today about 290 000 tonnes/year. With an estimated conservative capture rate of 90%, 261 000 tonnes of CO_2 will be captured per year. When taking periods of maintenance stops into account, the yearly operational time is set to 8400 hours, which gives the daily values as shown in Table 2-5.

Table 2-5 Dimensioning values for CO_2 generated and captured at Elkem Thamshavn.

		CO_2 generated	Capture rate	CO_2 captured
Yearly value (*)	tonnes/year	290 000	90 %	261 000
Daily value (**)	tonnes/day	829	90 %	746

(*) This is the amount of CO_2 generated and captured from the plant in average over a whole year. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture, compression, and liquefaction.
(**) CO_2 generated and captured per day is calculated from the yearly value and 8400 hours per year of operation when taking maintenance stops into account. This value is used further in the study as dimensioning capacity for the CO_2 capture, infrastructure, and transport chain, and for calculating required power (in MW) for CO_2 capture, compression, and liquefaction.

The CO_2 concentration measured in the stack is only about 4.5 vol%. There is a large amount of false air sucked into the off-gases downstream of the furnaces, about 40-50% of the total air. This false air is principally not needed and if it were avoided, the CO_2 concentration would increase up to 7.5 vol%. Such an increase would be highly beneficial for the capture process. The off-gases do also contain some other components and impurities. It might be necessary to clean the flue gas for NOx, SOx, and possibly also other impurities prior to an amine-based CO_2 capture plant.

The CO_2 stripper will need thermal energy in form of saturated steam at temperatures in the range 130 – 140°C (3 – 4 bara). With a modern amine solvent, such as AMP/PZ, thermal energy consumption could be around 3.3 MJ/kg CO_2 for the given CO_2 concentration, equivalent to 28.5 MW_{th} when using the daily dimensioning value for CO_2 captured. Since heat at rather low temperature is required for solvent regeneration, this is available on site. However, it will reduce the capacity for producing power and for supplying the district heat network.

The electric power requirement for a CO_2 capture, compression, and liquefaction plant at Elkem Thamshavn is, with a preliminary calculation using AMP/PZ, estimated to 3.9 MW_{el} when assuming compression and liquefaction of a pure CO_2 stream. This added power consumption is equivalent to only 4 % of the total furnace power consumption of 70 MW_{el} so there should be enough power available on-site.

The Elkem Thamshavn site has some available space in the north end, about 10 000 m^2, which can be used for a capture plant. A feasibility study made by Elkem shows how the capture plant, and the purification and liquefaction plant, can be placed here. An intermediate CO_2 storage for four days of production is also included in these plans. The further transport of the CO_2 to the permanent storage site will have to be undertaken by ship. However, the on-site quay capacity is limited. For most goods, Elkem is using a much larger harbour in Orkanger, about 1.5 – 2 km away, and truck transport in between. This is also a relevant option for the transport of CO_2. With a truck capacity of 35 tonnes of CO_2, about 21 truckloads per day (24 hours) will be needed to transport the 746 tonnes/day of captured CO_2.

Elkem Thamshavn has CO_2 allowances for 193 000 tonnes/year and must buy additional allowances for excess emissions. In order to reduce costs for allowances, increased use of biocarbon is one strategy. This might influence product quality and such a biocarbon increase must be investigated and implemented step by step. Another strategy is carbon capture and storage, CCS. However, the cost for CO_2 emissions must increase to make CCS economically feasible. Incentives that award capture of biogenic CO_2 do not exist as of today. This would be relevant for Elkem Thamshavn due to the use of biocarbon. Centrally, Elkem has a lot of ongoing activities on reducing CO_2 emissions, with CCS being one of the important technologies.

2.5 Wacker Chemicals Norway - Holla Metall

The WACKER group, with its main seat in Germany, employs around 14 300 people across the world, and had sales for € 4 692 million in 2020. The smelting plant at Holla was founded in 1964 and is situated at the sea front some 4 km north-east of Kyrksæterøra in Heim municipality. It became part of WACKER in 2010 and is today the only smelter in the WACKER group. The number of employees is approximately 230.

Wacker Holla Metall produces metallurgical grade silicon metal and microsilica. The annual production exceeds 70 000 tonnes/year of silicon, and more than 30 000 tonnes/year of microsilica. This is produced in four furnaces with electric power demand of 14, 18, 33, and 47 MW, respectively. In total 112 MW. The largest furnace was put in operation in 2019 and is among the largest silicon furnaces in the world.

The silicon from the smelter at Holla is being used by other affiliates internally in the WACKER group. Silicon metal is important to solar and semiconductor industries. Microsilica is formed as dust in the furnace and is separated in the filters. It is mainly used as an important admixture for concrete.

Figure 2-9 Wacker Chemicals Norway - Holla Metall.

The process at Holla similar to what is shown in Figure 2-8, except there is no energy recovery system. The main raw material is quartz (SiO_2). This is added to the furnaces together with a carbon source (hard coal and biocarbon) which acts as reduction material. The quartz is converted into liquid silicon that is tapped out of the furnace. The oxygen from the quartz and from the inflowing air reacts with the carbon in the reduction material to form CO_2. This is the source of the CO_2 being emitted from the plant.

The amount of air sucked into the furnace is primarily used to control the temperature. The off-gas out of the furnaces at Holla has a typical average temperature of about 700°C. Filter inlet temperatures are in the range 200 - 230°C. There is today no energy recovery from the furnace off-gases. The needed gas cooling is done by heat loss to the surrounding air from the off-gas steel pipes and in the so-called "trombone cooler". A large amount of heat is therefore available for a possible CO_2 capture plant.

The CO_2 emitted with the off-gases is 492 000 tonnes/year with the new 47 MW furnace included. With an estimated conservative capture rate of 90 %, about 442 000 tonnes of CO_2 per year will be captured. However, the dimensioning value for the capture plant and related infrastructure is better evaluated using daily values, considering that the yearly amount includes periods of lower or higher production. The plant is operating continuously the whole year around since the different furnaces are stopped for short maintenance at different times. The resulting values for CO_2 generated and captured are shown in Table 2-6.

Table 2-6 Dimensioning value for CO_2 generated and captured at Wacker Holla Metall.

		CO_2 generated	Capture rate	CO_2 captured
Yearly value (*)	tonnes/year	492 000	90 %	442 800
Daily value (**)	tonnes/day	1479	90 %	1331

(*) This is the amount of CO_2 generated in average over a whole year with the new 47 MW furnace in full operation. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture, compression, and liquefaction.
(**) CO_2 generated and captured per day is calculated from the yearly value with an added 10 % to reflect there are periods with somewhat higher production than the average value (based on data from 2021). This value is used further in the study as dimensioning capacity for the CO_2 capture, infrastructure, and transport chain, and for calculating required power (in MW) for CO_2 capture, compression, and liquefaction.

The capture plant will most likely be an amine-based plant where the amine solvent absorbs the CO_2 from the off-gas in the absorber tower, and where the CO_2 is released from the amine in the stripper tower and will be available as an almost pure CO_2 stream. Capture of CO_2 will have to be done downstream the filters to avoid the dust. The CO_2 concentration in the off-gases is low, in the range 1 – 5 vol%, where the higher values are achieved if the air leak into the filters can be reduced. Achieving the highest possible values are most beneficial for the capture process. The off-gases do also contain some other components and impurities. It might be necessary to clean the flue gas for NOx, SOx, and possibly also other impurities prior to an amine-based CO_2 capture plant.

The CO_2 stripper will need saturated steam at temperatures in the range 130 – 140°C (3 – 4 bara). With 1331 tonne/day of CO_2 captured, the stripper thermal power (heat) is preliminary estimated at 50.7 MW_{th} when using the modern AMP/PZ amine solvent. This is less than the heat being dumped to the surrounding air from cooling of the off-gases, which is about 60 MW_{th} for the two largest furnaces together. I.e., the required heat is available on-site.

The electric power requirement for a CO_2 capture, compression, and liquefaction plant at Holla is preliminary calculated to 6.9 MW_{el} when assuming compression and liquefaction of a pure CO_2 stream, and an AMP/PZ solvent. This will give a 6% increase compared to the total furnace electric power of 112 MW. The annual electric energy consumption, based on yearly CO_2 captured of 442 800 tonnes, is estimated at 55.1 GWh_{el} per year with the same assumptions as above.

The Holla site has good quay capacities for possible CO_2 ships where length and depth fulfil what is required in the Northern Lights FEED study (reference). There is no available space in the current industrial zone for a CO_2 capture plant. WACKER is in exchange with Heim municipality about options and respective frame conditions to enlarge the industrial zone adjacent to today's Holla site for potential further investments in operations.

WACKER sees that there is a necessity to handle the CO_2 generated today at Wacker Holla Metall, but also sees a need to understand more before an internal decision can be made on how to proceed with CCS. The available high-temperature off-gas and lack of energy recovery today indicates that there could be an interesting low-OPEX case for CO_2 capture. WACKER is in dialogue with Heim municipality about potential options to expand the industrial area, and about potential CCUS activities. WACKER has received some first positive feedback on this matter. On December 16, 2021, WACKER publicly launched its new and more ambitious sustainable development goals at Capital Markets Day: "To achieve an even more sustainable silicon-metal manufacturing process, the options of carbon capture and storage (CCS) and utilization (CCU) at Holla Metall will also be investigated".

2.6 Equinor Tjeldbergodden Methanol Plant

The methanol plant at Tjeldbergodden produces about 930 000 tonnes of methanol per year, being the largest in Europe. It is owned by Equinor with 82% and ConocoPhillips 18%. The Tjeldbergodden site also contains the Haltenpipe gas receiving facility and an air separation plant producing oxygen for the methanol process. The plants started operation in 1997 and employs about 125 people. The methanol is shipped directly to customers in Western Europe or to a transfer terminal in Rotterdam for further export. Methanol is a basic chemical that is used as a raw material in a long variety of chemicals, such as building materials, plastics, paint, solvents, and polyester, as well as a fuel or a fuel admixture, and as basis for producing new hydrocarbons.

The feedstock is natural gas from the Heidrun offshore field, with about 2 million Sm^3/day. The natural gas is converted to a syngas through three main stages: A pre-reformer, converting heavier hydrocarbons to methane, a steam-methane reformer (SMR) converting about 30% of the methane to syngas, and an auto-thermal reformer (ATR) converting the remaining methane. The ATR is using oxygen from the on-site air separation plant. The syngas out from the ATR goes further to the methanol process where first raw methanol is produced, and thereafter distilled to pure methanol.

Figure 2-10 Equinor Tjeldbergodden Methanol Plant.

Tjeldbergodden is one of the most energy efficient methanol plants in the world. The main energy source is natural gas being burnt in the SMR to provide heat to the process. The process stream is further heated through the ATR. The hot syngas after the ATR flows through an energy recovery system that produces steam which is used as process steam and for electric power production in a steam turbine. The steam turbine produces about 20-22 MW power during normal operation and makes the methanol plant self-supported with power with present production capacities. However, the plant is still connected to the main power grid and can both import and export power depending on the plant load. Excess power is also used by the air separation plant. An energy-containing purge-gas is produced as an off-gas from the methanol production. This gas is fed back and used as energy source in the process. Hot wastewater is recycled and re-used to minimise energy use and discharge to the sea. Waste heat from the process is used to heat seawater going to a nearby onshore fish farm. Remaining waste heat from the plant is dumped to the sea.

The CO_2 emissions from the methanol plant today amount to around 260 000 tonnes per year, where the emission source is the flue gas from the natural gas being burnt in the SMR. The CO_2 emissions are rather evenly distributed since the plant is usually operating at its nominal production capacity, and with a yearly operational time of about 97 – 98%. Occasionally the plant needs to be ramped down, however, minimum operating capacity is 80% of nominal value. Below this, the plant must be stopped. Every second year there is a main maintenance stop, reducing the operational time to about 87%. The capacity for a year without main maintenance stop is used as the dimensioning case for a CO_2 capture plant. The values are shown in Table 2-7.

The CO_2 concentration in the exhaust gas is in the range 8 – 10 vol%. There are few other impurities in the exhaust, except some NOx formed in the combustion process. A capture plant based on amine absorption is feasible, as confirmed by analysis at Test Centre Mongstad (TCM). A lot of low-temperature heat will be needed, and this might reduce the steam power production to some degree. Low-temperature CO_2 capture technology might also be an alternative, since there is a lot of available cooling capacity in the nitrogen stream from the cryogenic air separation plant.

Table 2-7 Dimensioning values for CO_2 generated and captured at Equinor Tjeldbergodden.

		CO_2 generated	Capture rate	CO_2 captured
Yearly value (*)	tonnes/year	260 000	92 %	240 000
Daily value (**)	tonnes/day	731	92 %	675

(*) This is the amount of CO_2 generated and captured from the plant in average over a whole year. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture and liquefaction.
(**) CO_2 generated and captured per day is calculated from the yearly value and operational time 8540 hours per year (97.5 % uptime) when taking maintenance stops into account. This value is used further in the study as dimensioning capacity for the CO_2 capture, infrastructure, and transport chain, and for calculating required power (in MW) for CO_2 capture and liquefaction.

There is a lot of available space that can be used for CO_2 capture, processing, and intermediate storage. Three different areas, each of about 20 000 m^2, has been marked as possible options. Quay capacity is good with two different quays that can be used, depending on the exact location of the capture plant and the on-site intermediate CO_2 storage that will be needed.

The capacity in the regional power grid is a possible bottleneck for increased power consumption at the Tjeldbergodden plant. There is regional work ongoing to look at possible solutions for how to cover future increases in power consumption at Tjeldbergodden and other regional industries.

A future business case for Tjeldbergodden Methanol Plant could be to shift the production towards low-carbon methanol. There are some different routes that can be followed. Methanol production with CO_2 capture and storage (CCS) is one of them. Added cost with CCS will have to be compensated by the costs for CO_2 emissions if CCS was not implemented, and a possible higher price for low-carbon methanol in a marked where demand for low-carbon goods and products is increasing.

2.7 Summary of CO_2 generated and captured

The yearly and daily values for CO_2 generated and captured are summarized in Table 2-8. As noted in the former sub-chapters, the yearly values are used as basis for calculating yearly electric and thermal energy consumption for CO_2 capture, compression, and liquefaction. The daily values are generally higher than the yearly values divided by 365 days, to reflect that there are maintenance stops, revisions, and that some of the plants can operate at higher production capacity for periods. These daily values are the relevant ones to use as the design capacity of the CO_2 capture plant and infrastructure, electric and thermal power capacity, and for the dimensioning the CO_2 transport chains and logistics planning.

2.8 Summary of power requirements and annual energy consumption

There is limited capacity in the possible electric power supply to some of the plants. Some preliminary estimates for electric power requirements for CO_2 capture, compression, and liquefaction have therefore been done. The assumed capture technology is membrane capture for Verdalskalk and NorFraKalk. For Statkraft Varme a solution for amine capture that takes into account that there will be no steam available for the capture process/plant is assumed. For the three other plants, AMP/PZ is assumed as an indicative technology, to provide a rough estimate of heat and power consumption on site. The CO_2 concentrations are as described in the former sub-chapters, and they are summarized in Table 2-9.

The specific electricity consumption for the membrane capture plants have been provided by Franzefoss Minerals based on vendor information, and they include the electricity needed for CO_2 capture, compression, and liquefaction. The value is 417 kWh/tonne CO_2 captured for Verdalskalk, and 366 kWh/tonne CO_2 captured for NorFraKalk. The smaller value for NorFraKalk is due to the somewhat higher CO_2 concentration.

The specific electricity consumption for the AMP/PZ amine capture plants is found from calculated data in literature. They depend much on the CO_2 concentration where higher concentrations need lower specific electricity. For the four amine plants in discussion here the figures range from 13 – 33 kWh/tonne CO_2 captured. As for the membrane plants, the electricity for CO_2 compression and liquefaction must be included. The electric power needed for this is found in Deng et al.[3]. For a pure CO_2 stream with inlet conditions 1 bar and 40°C, being compressed and liquefied to 15 bar and -28°C, the specific electricity consumption is 91 kWh/tonne CO_2. The actual CO_2 streams from the capture plants will contain some small amounts of impurities. These might increase the power consumption for compression and liquefaction, but due to the small amounts of impurities, the value for pure CO_2 is used here to get an estimate. The total specific electricity consumption for CO_2 capture, compression, and liquefaction for the four AMP/PZ amine capture plants will then be in the range 104 – 124 kWh/tonne CO_2 captured.

The specific electricity consumption values for the amine plants are much smaller than for the membrane plants. However, the amine plants need a large amount of thermal energy (heat) to regenerate the amine in the CO_2 stripper. The specific thermal energy consumption is a function of CO_2 concentrations, where higher concentrations give lower specific thermal energy requirements. For the four plants in this study, the specific thermal energy consumption is in the range 810 – 920 kWh/tonne CO_2 captured when using the modern AMP/PZ amine. The required thermal energy (heat) for each plant is included in Table 2-9, both the required thermal power (in MW_{th}) and the annual heat consumption (in GWh_{th}/year). These values are included to illustrate the proportions between electric and thermal energy consumption when applying amine technology.

---

[3] Han Deng, Simon Roussanaly, Geir Skaugen. Techno-economic analyses of CO2 liquefaction: Impact of product pressure and impurities. International Journal of Refrigeration (2019).

Table 2-8 Dimensioning values for CO_2 generated and CO_2 captured – overview for all plants.

		Verdalskalk	**NorFraKalk**	**Statkraft Varme Heimdal**	**Elkem Thamshavn**	**Wacker Holla Metall**	**Equinor Tjeldberg-odden**	**Sum**
CO_2 generated – annual value [(A)]	*tons/year*	55 000	174 000	240 000	290 000	492 000	260 000	1 511 000
CO_2 capture rate	*%*	90	90	90	90	90	92	
CO_2 captured – annual value [(B)]	*tons/year*	49 500	156 600	216 000	261 000	442 800	240 000	1 365 900
CO_2 generated – daily value [(C)]	*tons/day*	192	670	658	829	1 479	731	4 559
CO_2 captured – daily value [(D)]	*tons/day*	**173**	**603**	**592**	**746**	**1 331**	**675**	**4 120**

(A) This is the normal amount of CO_2 being released from the plant per year, based on recent data.
(B) This is the CO_2 that will be captured per year with the given capture rates. This value is used to calculate required yearly energy consumption (in GWh) for CO_2 capture, compression, and liquefaction.
(C) This is a representative amount of CO_2 that can be generated per day over a period of one to several weeks. The daily values are generally somewhat higher than the annual value divided by 365 days since they include that the plants do not have 100% full operating time due to stops for maintenance, and some of the plants also have larger production capacity than what is normally utilised and in periods can produce more, generating more CO_2, which are then relevant to use as the dimensioning value.
(D) This value is based on the daily generated CO_2 value above and the given capture rates. This is the relevant dimensioning capacity for the capture plant and the CO_2 infrastructure needed on each site, as well as for the transport chains. It is also used for calculating required power (in MW) for CO_2 capture, compression, and liquefaction.

Table 2-9 Estimated power requirements and annual energy consumptions for CO_2 capture, compression, and liquefaction.

		Verdalskalk	**NorFraKalk**	**Statkraft Varme Heimdal**	**Elkem Thamshavn**	**Wacker Holla Metall**	**Equinor Tjeldberg-odden**	**Sum**
Assumed capture technology (A)		Membrane	Membrane	Amine solution	AMP/PZ	AMP/PZ	AMP/PZ	
Typical CO_2 concentration (B)	*%*	20	25	11.0	4.5	4.5	9.0	
Electric power requirement(C)	MW_{el}	3.0	9.2	3.5	3.9	6.9	3.1	29.6
Thermal power (heat) requirement (D)	MW_{th}	-	-	27.0	28.5	50.7	23.1	
Annual electric energy consumption (E)	GWh_{el}*/year*	20.6	57.3	30.6	32.5	55.1	26.5	222.6
Annual thermal energy (heat) consumption (F)	GWh_{th}*/year*	-	-	236	239	405	197	

(A) The assumed technology is indicative only, and used to provide a rough estimate of power consumption on site.

(B) Representative CO_2 concentrations for each plant, used for calculating energy requirements.

(C) Calculated based on the daily captured CO_2 values from Table 2-8 *and specific energy requirements according to CO_2 concentration and capture technology.*

(D) Calculated as done for (C). Included to illustrate the proportions between electric and thermal power consumption when applying amine technology. It is not specified in the table if the heat is provided from heat recovery or if heat supply is provided from external sources.

(E) Calculated based on annually captured CO_2 values from Table 2-8 *and specific energy requirements according to CO_2 concentration and capture technology.*

(F) Calculated as done for (E). Included to illustrate the proportions between electric and thermal power consumption when applying amine technology. For thermal energy, the same comment applies as described for thermal power in point (D).

NOTE! *Electric power and electric energy consumptions are calculated assuming compression and liquefaction of a pure CO_2 stream to 15 bar.*

3 CO_2 logistics

3.1 Shipping conditions

The six industrial plants in the CCS Midt-Norge project lay scattered along the Mid-Norway coastline and the Trondheim fjord as shown in Figure 3-1. The Northern Lights (NL) CO_2 terminal close to Bergen (cf. Figure 3-1) is the first option to consider for delivering the captured CO_2 for permanent storage. The long distance to the NL terminal, as well as the scattered location of the six plants, imply a major importance of optimal planning of the CO_2 logistics, to minimize the CO_2 transport costs. This report, therefore, investigates potential CO_2 logistics options for the six plants in the CCS Midt-Norge project, to identify cost-effective solutions for a common CO_2 transport infrastructure.

In the logistics planning, ship transport is considered the most relevant method for transporting CO_2 from the plants. The only exception is Statkraft Varme Heimdal, which is located on the inland near Trondheim. The CO_2 from the Statkraft plant is assumed to be delivered by truck to Orkanger port, close to Elkem Thamshavn, before being transported by ship.

Due to the long distance to the NL terminal, two possible alternative offshore CO_2 terminals outside Mid-Norway ("Mid-Norway offshore terminal 1 and 2" in Figure 3-1) have also been evaluated, to see if these options could reduce CO_2 transport costs for the Mid-Norway industrial plants.

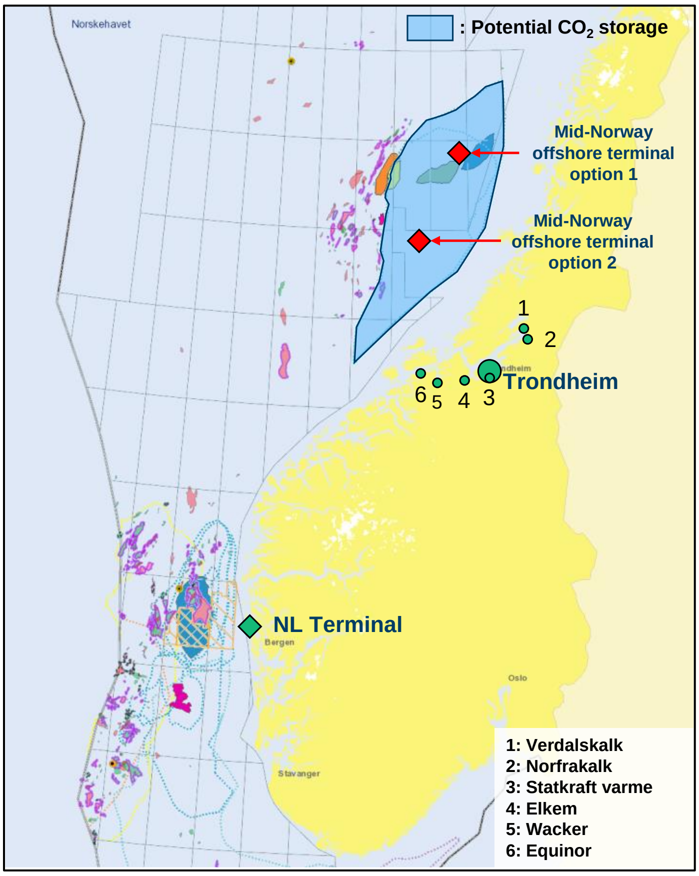

Figure 3-1 Location of the Northern Lights (NL) CO_2 terminal, the six plants in the "CCS Midt-Norge" project and potential offshore CO_2 terminals outside Mid-Norway *(map adopted from https://factmaps.npd.no)*

Table 3-1 Shipping data for the six plants when using the Northern Lights (NL) terminal.

Ship transport	Unit	Verdalskalk	NorFraKalk	Statkraft[f]	Elkem	Wacker	Equinor
Quay depth[a]	[m]	2-5	7-9	9	9	10-20	15
CO_2 ship draft[4]	[m]	8.50	8.50	8.50	8.50	8.50	8.50
Sailing to NL[b]	[km]	600	593	533	532	470	433
Stops	[-]	1	1	1	1	1	1
Round-trip[c]	[d]	2.9	2.9	2.7	2.7	2.5	2.4
Captured CO_2[d]	[t/d]	173	603	592	746	1331	759[g]
	[m^3/d]	163	570	560	706	1259	718[h]
4d buffer storage[e]	[m^3]	750	2500	2250	3000	5250	3000
NL ship size	[m^3]	7500	7500	7500	7500	7500	7500

[a] https://www.norgeskart.no.
[b] https://searoutes.com.
[c] 12 hours of loading time and 12 hours of unloading time (including arrival, connection, etc.). 14 knot ship speed.
[d] Density of 15 barg liquid CO_2: 1057.2kg/m^3.
[e] The on-site buffer tank has a capacity of 4 days of CO_2 storage and is rounded-up to nearest 250 m^3.
[f] The buffer storage is not including the 750 m^3 of buffer tank for trucks at Statkraft Varme Heimdal.
[g] In the most recent base case for Tjeldbergodden, this value will be 675 tonnes/day. This information was not available when doing the logistics calculations here in Chapter 3, so 759 tonnes/day was used.
[h] With 675 tonnes/day, this value will be 638 m^3/day. However, 718 m^3/day was used in the calculations in the logistics calculations here in Chapter 3 for same reason as described in comment given above.

For ship transport of the CO_2, each plant site is assumed to have a quay for loading of the intermediately stored CO_2. Statkraft Heimdal Varme is assumed to use one of the quays at the Orkanger port. It should be noted that the quay depth at Verdalskalk is relatively shallow compared to the draft of the Northern Lights CO_2 ships, as shown in Table 3-1. Thus, a marine structure will be required to extend the quay towards the sea in order to ensure the water depth for CO_2 ships.

The actual sailing distance from the plant sites to the NL terminal is between 433 and 600 km, requiring more than two days for the round-trip. To the estimation of the round-trip time, 12 hours of loading and 12 hours of unloading time is considered, which includes the time for arrival, connection, loading/unloading, disconnection, and departure. Consequently, the capacity of on-site CO_2 buffer tanks needs to be sufficient to store the captured CO_2 for several days. It is worth noting that the buffer storage, transport capacity, and logistics planning are based on the daily CO_2 capture values from the plant analysis performed in Chapter 2. For four days of storage, which is the period considered by other sites planning to deliver CO_2 to the NL terminal, the tank size of each site is smaller than the cargo capacity of the NL CO_2 ship (7500 m^3 of liquid CO_2). This implies that the ship is oversized for the six plants in the study, or that the buffer storage period of four days is not suitable for efficient utilization of the cargo capacity. The size of the buffer tanks and the cargo capacity of the CO_2 ships are therefore key parameters for the development of optimal CO_2 logistics.

In this logistics planning, local offshore CO_2 storage terminals outside Mid-Norway can be considered as an option to the NL terminal, to reduce the sailing distance and transport costs. Potential solutions for such offshore CO_2 terminals can be floating CO_2 storage and injection units (FSU), offshore platforms, and direct

---

[4] Equinor. Northern Lights FEED Report: RE-PM673-00057. https://Northernlightsccs.Com/En/Facts-and-Reports: 2020.

injection from the CO_2 transport ship. Figure 3-1 presents two potential CO_2 offshore terminals outside Mid-Norway, which are about 150-200 km closer than the NL terminal. The shorter sailing distance will contribute to reducing the round-trip time, affecting the optimal size of buffer tanks and CO_2 ships.

3.2 Shipping route scenarios for CO_2 transport to Northern Lights terminal

With six different sites and CO_2 emission levels, several shipping plans can be made as shown in Table 3-2. In scenario 1, each site has its own ship to deliver CO_2 to the NL terminal, resulting in six individual shipping routes. Other scenarios show different ways of linking the target sites. Scenario 2 binds two and two plants, which gives three shipping routes. Scenarios 3 and 4 have two shipping routes by binding four and five sites respectively. Scenario 5 assumes that a ship will stop at each site, resulting in only one shipping route. Based on the shipping routes, each scenario has different sailing distances and number of stops for loading, which will affect the round-trip time and the transport cost. The purpose of such binding strategies is to assess the benefits of joint efforts in CO_2 logistics and to seek the most economically viable solution to accelerate the deployment of CCS infrastructure in Mid-Norway.

Table 3-2 Scenarios for shipping routes from the six industrial plants to the NL terminal.

Scenario	Binding [-]	Sailing [km]	Stops [-]	Round-trip[a] [days]
Scenario 1	Ve / No / St / El / Wa / Eq	600/593/533/532/470/433	1/1/1/1/1/1	2.9/2.9/2.7/2.7/2.5/2.4
Scenario 2	Ve+No / St+El /Wa+Eq	600/532/474	2/1/2	3.4/2.7/3.0
Scenario 3	Ve+No+St+El / Wa+Eq	632/474	3/1	4.0/3.0
Scenario 4	Ve+No+St+El+Wa / Eq	668/433	4/1	4.6/2.4
Scenario 5	Ve+No+St+El+Wa+Eq	672	5	5.2

Ve=Verdalskalk, No=NorFraKalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.

[a] 12 hours of loading and 12 hours of unloading time. 14 knot ship speed.

The logistics planning is determined by the shipping routes as well as the size of local buffer tanks and CO_2 ships. In this work, two different shipping conditions are considered for each scenario. Condition 1 (the NL condition, “NL cond”) is used as a reference. Here the size of the CO_2 ships is fixed to the Northern Lights size of 7500 m^3, and buffer tanks are fixed to 4-day storage of captured CO_2, respectively. These are the conditions applied by Northern Lights in the Longship project for Norcem Brevik and Hafslund Oslo Celsio (Klemetsrud). In Condition 2 (the optimal condition, “Opt cond”), different ship sizes are tested while the buffer tank capacity is assumed to be either four days of CO_2 capture, or 25% larger than the NL ship size, or 25% larger than the actual ship size (see Table 3-3 for details). For this condition, a large number of options have therefore been evaluated for each of the five scenarios, and the one performing best for each scenario has been chosen and are presented in the results to follow. It should be noted that the optimal ship and buffer tank sizes may, in some cases, be identical to the NL condition.

Table 3-3 The two main shipping conditions for CO_2 logistics planning.

Condition	Ship size [m^3]	Total buffer tank size [m^3]
(1) Northern Lights ship size + 4 days buffer storage (the NL condition, “NL cond”)	7500	- 4 days × daily captured CO_2
(2) Optimal ship size + optimal buffer storage (the optimal condition, “Opt cond”)	1250 - 10000	- 4 days × daily captured CO_2 - 1.25 times of NL ship (1.25 x 7500) - 1.25 times of optimal ship size

In the economic analysis, the scope of work is limited to the transport chain between the local on-site storage tanks and the NL terminal in order to focus on CO_2 logistics (see Figure 3-2 and Figure 3-3 for details). Transport costs include capital and operating expenditures (CAPEX and OPEX) for the local storage tanks, local loading/unloading facilities, trucks, and ships, and ship fuel and local harbour costs. No costs at the receiving facility are included. The evaluated costs are for the transport chain up to the point where the ships arrive the terminal. It is assumed that captured CO_2 is liquefied and stored at 15 barg. Accordingly, the operating pressure level of the CO_2 tanks, trucks, and ships is set at 15 barg. All the facilities related to transportation are assumed to be operated for 25 years. The cost evaluation and the optimization of ship and tank sizes are carried out by the iCCS[5,6] tool from SINTEF Energy Research.

Due to the truck transport, the Statkraft Varme Heimdal route has different boundary conditions compared to the ship transport. Figure 3-3 shows that Statkraft Varme Heimdal requires additional infrastructure related to truck transport, such as trucks, on-site storage tanks, on-site loading facilities, and unloading facilities at the Port of Orkanger. The truck capacity is assumed to be 30 tonnes of liquid CO_2 at 15 barg. Except for Scenario 1, where each site uses an individual shipping route, the ship-related infrastructure for Elkem Thamshavn is assumed to be shared with Statkraft Varme Heimdal.

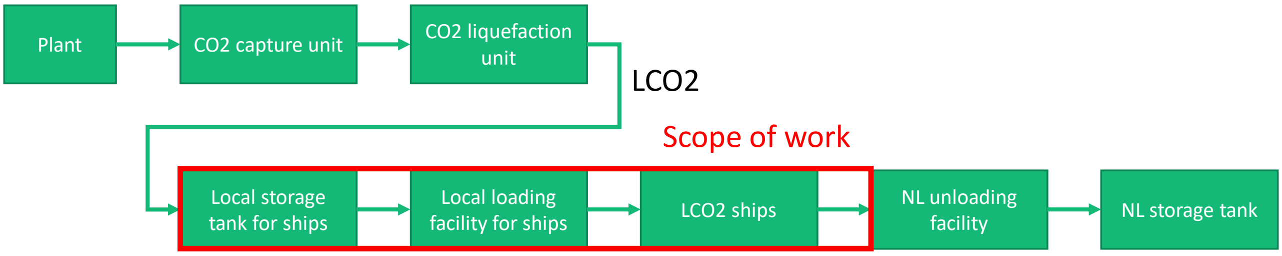

Figure 3-2 Scope of work for the ship transport.

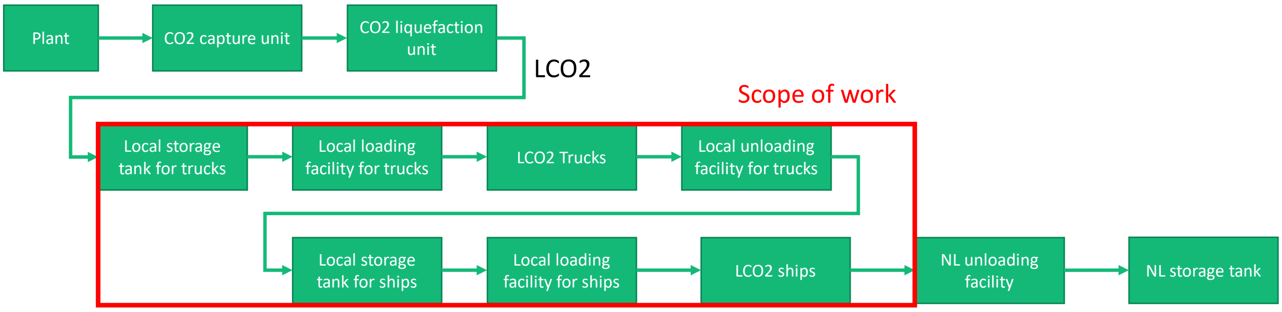

Figure 3-3 Scope of work for the combined truck and ship transport (Statkraft Varme Heimdal).

---

[5] Jakobsen J, Roussanaly S, Anantharaman R. A techno-economic case study of CO2 capture, transport and storage chain from a cement plant in Norway. Journal of Cleaner Production 2017;144:523–39.

[6] Roussanaly S, Deng H, Skaugen G, Gundersen T. At what Pressure Shall CO2 Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 barg Shipping. Energies 2021;14:5635.

3.3 Results of shipping scenarios

Figure 3-4 shows the results of CO_2 logistics with different scenarios and shipping conditions for the industries in the CCS Midt-Norge project, when the CO_2 is to be delivered to the Northern Lights (NL) terminal. The economic analysis indicates that the average transport costs[7] vary significantly from 18 to 42 €/$tCO2_{transported}$ dependent on the scenario and shipping conditions. Scenario 1, where individual shipping routes are considered, gives the highest transport cost regardless of the shipping condition and requires the largest number of ships for the logistics. Instead, other scenarios utilizing shared shipping routes show lower average transport costs compared to Scenario 1. This implies that joint efforts are essential to reduce the CO_2 transport cost for industries in the CCS Midt-Norge project.

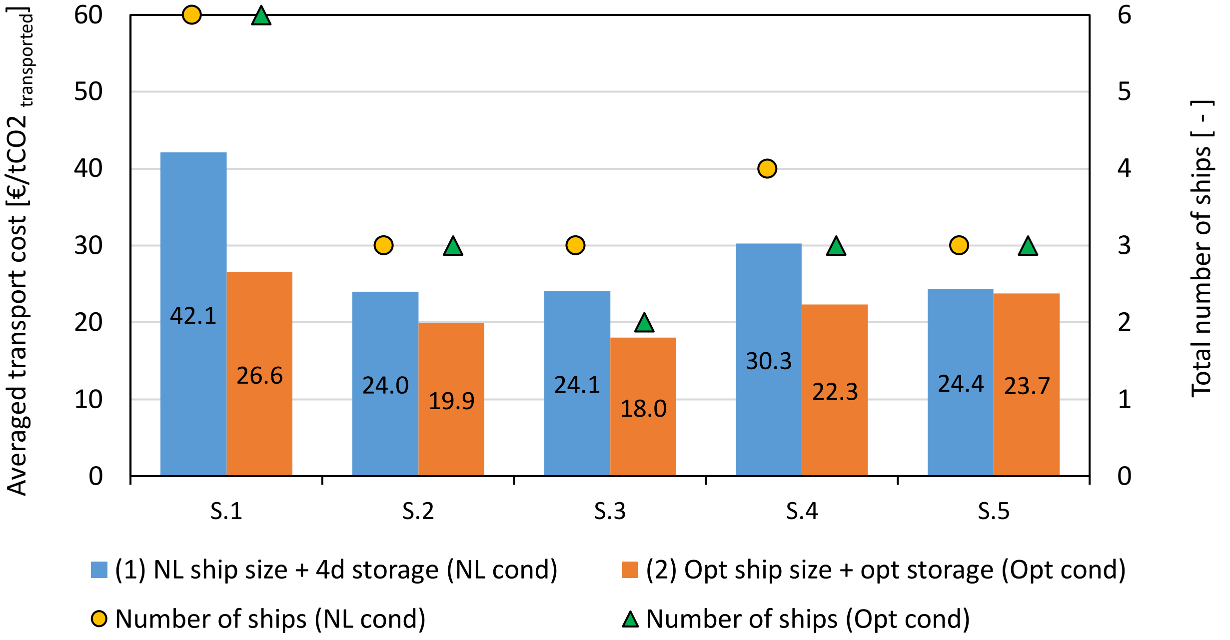

Figure 3-4 Transport cost of logistics scenarios for the industries in the CCS Midt-Norge project.

Regarding logistics planning, the average transport costs are relatively low when binding two (Scenario 2) and four plants (Scenario 3). Linking more than four plants (Scenario 4 and Scenario 5) causes a sharp increase in the number of ships and transport costs. Such bindings result in the round-trip time even longer than four days due to the larger number of stops and increased sailing distance as indicated in Table 3-2. To cope with the long round-trip time, either the size of the on-site buffer tank needs to be larger to store the captured CO_2 until the ship arrives, or a larger number of ships is required to collect liquid CO_2 before the tank is fully filled. Thus, the optimal logistics needs to be determined in accordance with the sailing plan (distance and stops) and shipping conditions (the buffer tank size and the cargo capacity of the CO_2 ship), which have an impact on the round-trip time and the transport costs.

The economic analysis with different shipping conditions shows that the NL condition (7500 m^3 ship and 4-day buffer tank) is not optimal for all the scenarios evaluated. The optimal size of the ship and storage tanks result in cost savings from 0.7 to 15.5 €/$tCO2_{transported}$ while reducing the number of ships in Scenario 3 and 4. In particular, Scenario 1 with the NL condition gives the highest transport cost, which again

---

[7] Average cost for 6 plants considering the amount of CO_2 transported from each site.

highlights individual shipping is not a favourable option for CO_2 logistics for the plants in the CCS Midt-Norge project.

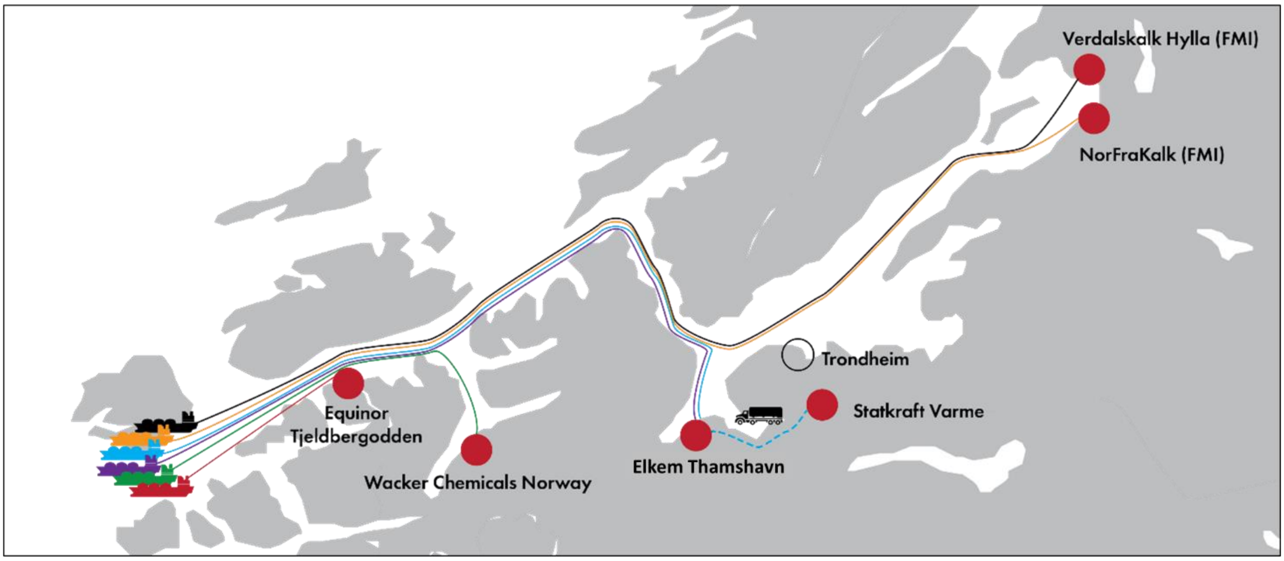

Figure 3-5 Individual shipping routes (Scenario 1).

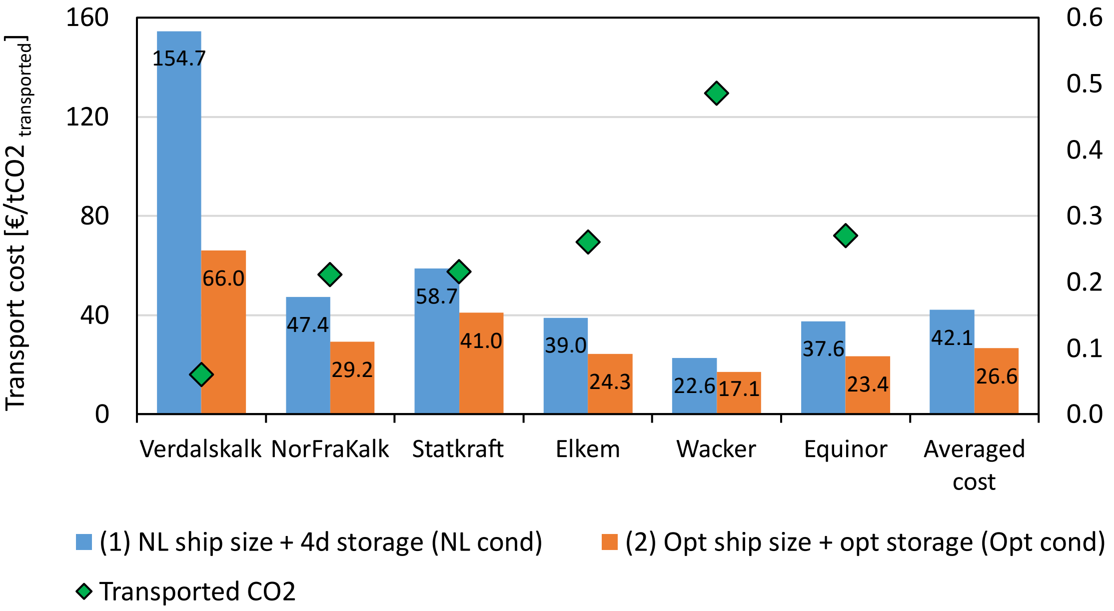

Figure 3-6 Transport cost of individual shipping routes (i.e., Scenario 1).

One of the reasons for the high transport cost of Scenario 1 is the economies of scale. As shown in Figure 3-6, each site has a different amount of CO_2 to transport, and the cost of shipping is approximately inversely proportional to the transport volume, except for Statkraft. The relatively high transport cost for Statkraft compared to NorFraKalk, which has almost the same CO_2 volume, is due to the additional truck transport costs. Without sharing the shipping route, the CO_2 transport volume of each route remains relatively small, increasing the unit capital cost due to the economies of scale.

Scenario 1 also shows large cost savings with the optimal ship and buffer tank size compared to the NL conditions. As presented in Table 3-4, the 4-day buffer tank size is significantly smaller than the cargo capacity of the NL ship. The NL ship is therefore oversized for the industrial sites in the CCS Midt-Norge project in the Scenario 1. Hence, in the optimal shipping conditions, smaller ship sizes are selected in order to cut down the transport cost. The optimal shipping conditions for Wacker also show that the buffer tank size can be reduced from the NL condition (storage capacity for four days). Nevertheless, the reduced ship and tank size means that the unit capital cost of the ship is increased. Therefore, the transport cost of each site with the optimal shipping conditions remains inversely proportional to the transport volume.

Table 3-4 also indicates that each site in Scenario 1 requires at least one ship to transport CO_2, resulting in a total of six ships and significant capital investment for the ships (see Table A-1 in Appendix for detailed information). Compared to other scenarios in Figure 3-4, the total number of ships required for Scenario 1 is almost doubled. However, if the shipping route is shared (Scenario 2 to 5), there is an opportunity to reduce the number of ships.

Table 3-4 The size of the buffer tank and CO_2 ship in individual shipping routes (Scenario 1).

Condition	Route	CO_2 captured [m^3/d]	Sail [km]	Stops [-]	Round trip[a] [d]	Buffer tank[b] [m^3]	Ship size [m^3]	Number of ships [-]
(1) NL cond	Verdalskalk	163	600	1	2.9	750	7500	1
	NorFraKalk	570	593	1	2.9	2500	7500	1
	Statkraft	560	533	1	2.7	2250[c]	7500	1
	Elkem	705	532	1	2.7	3000	7500	1
	Wacker	1259	470	1	2.5	5250	7500	1
	Equinor	718[d]	433	1	2.4	3000	7500	1
(2) Opt cond	Verdalskalk	163	600	1	2.9	750	1250	1
	NorFraKalk	570	593	1	2.9	2500	2500	1
	Statkraft	560	533	1	2.7	2250[c]	2500	1
	Elkem	705	532	1	2.7	3000	2500	1
	Wacker	1259	470	1	2.5	4750	3750	1
	Equinor	718[d]	433	1	2.4	3000	2500	1

[a] 12 hours of loading and 12 hours of unloading time. 14 knot ship speed.

[b] The tank size at each site is rounded-up to nearest 250 m^3.

[c] The tank size is not including the 750 m^3 of buffer tank for trucks at Statkraft Varme Heimdal.

[d] In the most recent base case for Tjeldbergodden, this value will be 638 m^3/day. This information was not available when doing the logistics calculations here in Chapter 3, so 718 m^3/day was used.

The economic analysis of Scenario 1, therefore, indicates that the key measures to reduce the transport costs are aiming for a large size ship that can stop by several sites to handle a large quantity of CO_2 and to take advantage of the economies of scale while looking for a chance to minimize the number of ships via the shared shipping route.

Consequently, Scenario 3, which combines four and two sites (cf. Figure 3-7), shows significant reductions in transport costs compared to Scenario 1. As presented in **Error! Reference source not found.**, if Verdalskalk, NorFraKalk, Statkraft, and Elkem cooperate for a common CO_2 transport infrastructure, the shipping costs can be 32 and 21 €/$tCO2_{transported}$ for the NL and optimal shipping conditions, which is at least 13% lower than their individual routes. Thus, the cooperation reduces the transport costs for all sites. The same trend can be seen for the combined route for Wacker and Equinor.

To further reduce transport costs, the two shipping routes in Scenario 3 can be owned and operated by all six industrial sites together, resulting in an average transport cost of 18 €/$tCO2_{transported}$ as seen in Figure 3-8. It is, however, worth noting that Wacker does not benefit from the average cost of Scenario 3 since the expense is higher than its individual route as shown in Figure 3-6. Nevertheless, the transport cost of the shipping route, which binds Wacker and Equinor, is still lower than the individual route of Wacker, justifying the need for cooperation.

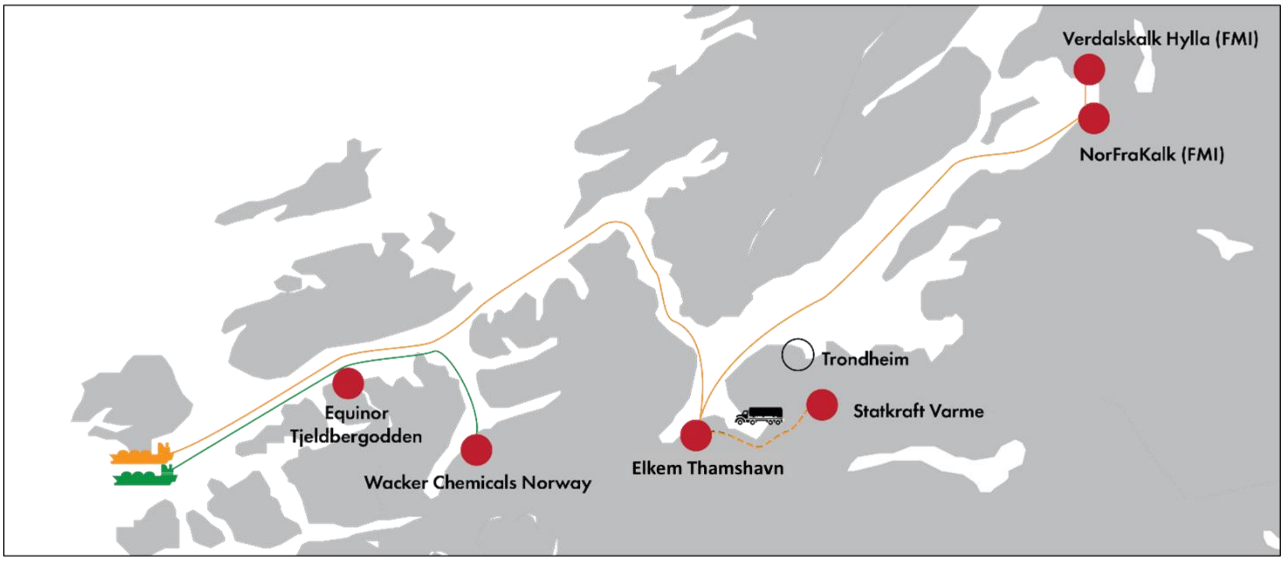

Figure 3-7 The two shipping routes in Scenario 3.

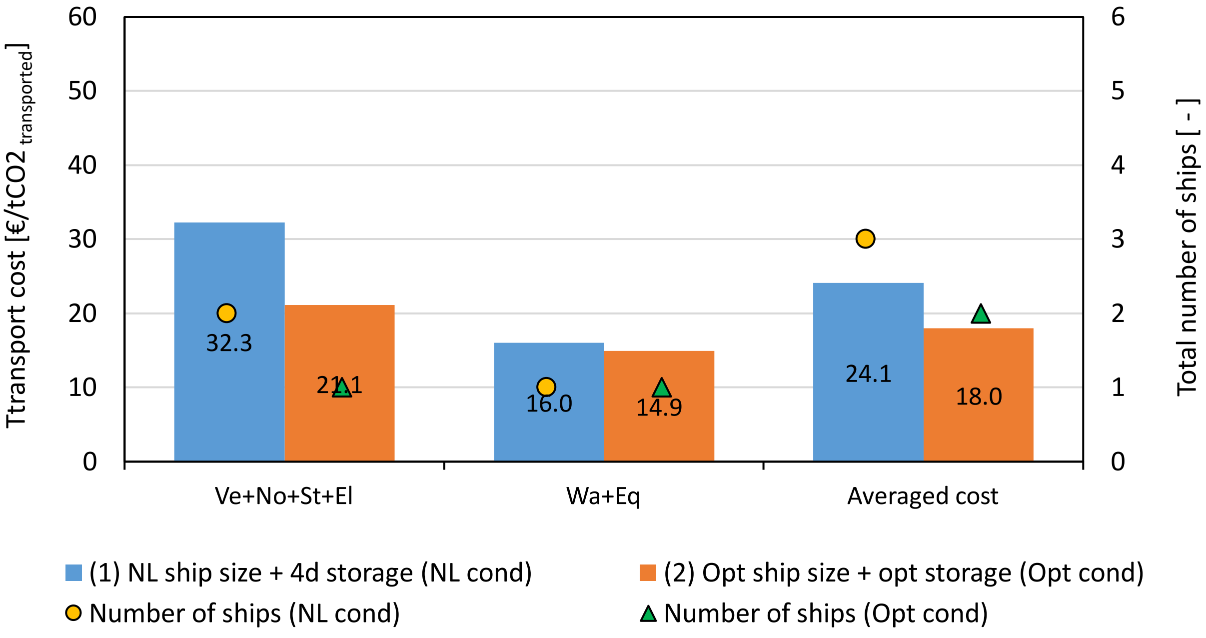

Figure 3-8 Transport cost of Scenario 3 and the number of ships.

As shown in Table 3-5, the shipping route for Verdalskalk, NorFraKalk, Statkraft, and Elkem needs a round-trip time of four days due to the increased sailing distance and the number of stops. This means that the

NL ship size (7500 m^3) is not sufficient for the total CO_2 stored for four days (approximately 8000 m^3), resulting in several ships collecting CO_2 at each site within four days. Instead, the ship size is increased to 8750 m^3 in the optimal condition in order to maintain single-ship operation while reducing the transport costs by 35%.

For the shipping route of Wacker and Equinor, there is no reduction in the number of ships with the optimal shipping conditions compared to the NL conditions, since the round-trip takes less than four days. However, the round-trip time of three days means that the NL ship is oversized for the two plants. Considering the total CO_2 shipping volume (about 2000 m^3/d) and the round-trip time (three days), the ship size can also be reduced below 7500 m^3 for this shipping route.

Table 3-5 The size of the buffer tank and CO_2 carrier in Scenario 3.

Condition	Route	CO_2 captured [m^3/d]	Sail [km]	Stops [-]	Round trip[a] [d]	Total buffer tank[b] [m^3]	Ship size [m^3]	Number of ships [-]
(1) NL cond	Ve+No+St+El	1999	632	3	4.0	8500[c]	7500	2
	Wa+Eq	1977	474	2	3.0	8250	7500	1
(2) Opt cond	Ve+No+St+El	1999	632	3	4.0	8500[c]	8750	1
	Wa+Eq	1977	474	2	3.0	8000	6250	1

Ve=Verdalskalk, No=Norfrakalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.

[a] 12 hours of loading and 12 hours of unloading time. 14 knot ship speed.

[b] The tank size at each site is rounded-up to nearest 250 m^3.

[c] The tank size is not including the 750 m^3 of buffer tank for trucks at Statkraft Varme Heimdal.

Thus, the optimal shipping conditions for Scenario 3 offer a smaller overall number of ships compared to the NL conditions, from a total of three ships to two ships, reducing the transport cost by 6.1 €/$tCO2_{transported}$ (see Figure 3-4 and Table A-2 in Appendix for detailed information). It should be noted that the difference between the NL and optimal shipping conditions becomes marginal when the required buffer tank size for a given round-trip time is close to the cargo capacity of the NL CO_2 ships.

From all the above results, Scenario 3 seems to be the best logistics plan for transporting the CO_2 from the six plants in the CCS Midt-Norge project to the NL terminal. Scenario 3 with the optimal shipping conditions (i.e., optimal ship size and optimal on-site buffer storage) gives the lowest average transport cost and lowest number of ships of all scenarios and conditions evaluated. In the following, Scenario 3 will be used as basis for evaluating some possible alternative logistic solutions, aiming at further reduction in CO_2 transport cost.

3.4 Alternative local offshore CO_2 terminals

As an alternative measure, local offshore CO_2 terminals that are closer than the NL terminal were considered in this work to possibly reduce the round-trip time and the transport cost for the best logistics plan (Scenario 3). Figure 3-9 shows the results of Scenario 3 with two alternatives for offshore CO_2 unloading terminals that can be located outside of Mid-Norway as shown in Figure 3-1. The results for Scenario 3 using the NL terminal from Figure 3-8 is included to the left for reference. Mid-Norway terminal (MN) 1 and 2 are approximately 270 and 200 km away from Trondheim while the shipping distance to the NL terminal is about 530 km.

It should be noted that the total time for offshore unloading could be much longer than time at quay at the NL terminal. The total unloading sequence includes time for arrival, connection, unloading, disconnection, and departure. Most of these steps will require more care and time when being done offshore. It is here estimated that a total of 36 hours will be needed for the unloading. If offshore unloading will become a relevant solution for CCS deployment, it can be anticipated that technology development might reduce offshore unloading time. Alternatives with 12 hours offshore unloading have therefore been evaluated as a comparison, using the same unloading time as for the NL terminal.

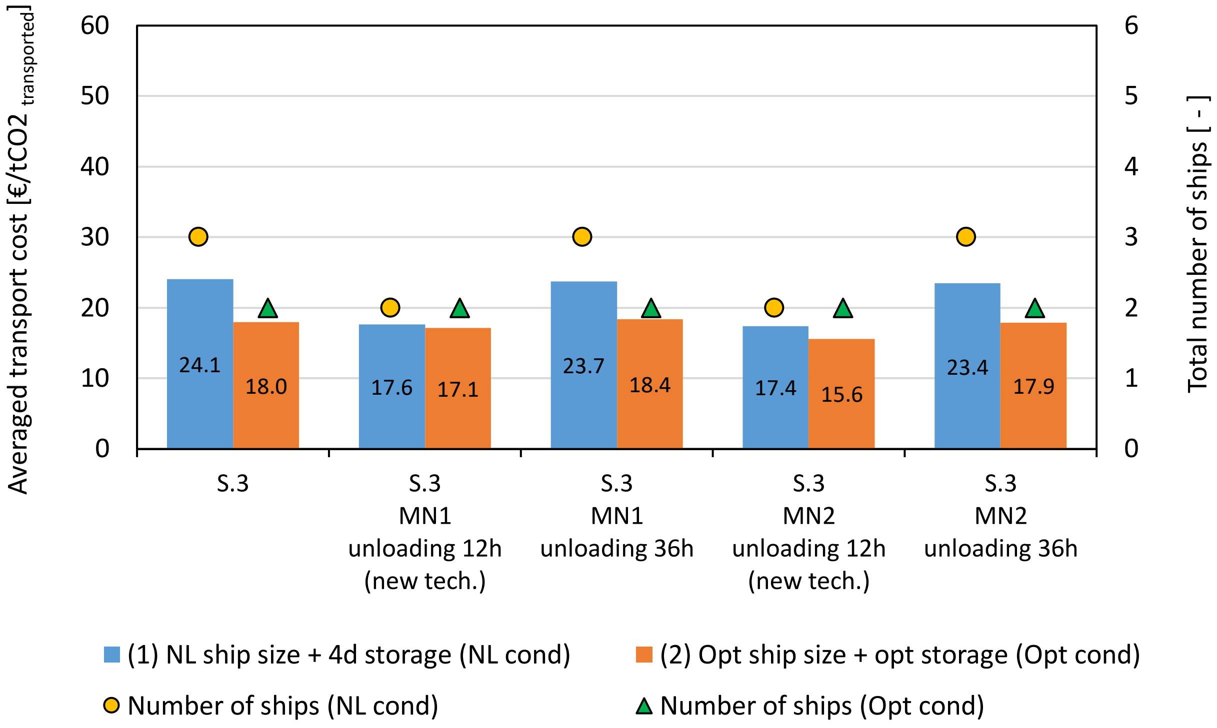

Figure 3-9 Options to reduce transport cost of Scenario 3: two alternative terminals (MN1 and MN2).

Compared to the NL terminal, neither of the two local terminals improves the economic performance of Scenario 3 with 36 hours of typical offshore unloading time, showing only a marginal decrease in the average transport cost for the MN2 terminal with the same number of ships. The transport cost of MN1 with optimal shipping conditions is even higher than that of the NL terminal.

The main reason for the low economic performance of the local offshore terminals is the increased round-trip time as shown in Table 3-6. Due to the longer round-trip time, the optimal ship size is increased compared to Scenario 3 with the NL terminal, which requires higher transport costs. Although the sailing distance to the local terminals is reduced by 29% - 35% compared to the NL terminal, the longer unloading time (36 hours) at the offshore facilities compared to the onshore terminal (12 hours) results in the increased round-trip time.

If the unloading time is reduced with technology development, for example to 12 hours, the transport cost can be lower than Scenario 3 by 0.9 €/$tCO2_{transported}$ with MN1 and by 2.4 €/$tCO2_{transported}$ with MN2 under optimal shipping conditions. As indicated in Table 3-6, the reduced unloading time leads to a decrease in the round-trip time and the size of the CO_2 ships, cutting the transport cost. However, the cost savings from reduced unloading time may not be sufficient to justify the additional cost required for offshore facilities, which are often capital-intensive. Therefore, the local offshore CO_2 terminals do not appear to be a significantly more attractive solution for the industries in the CCS Midt-Norge project compared to a location close to Bergen/Northern Lights, even if the offshore unloading time is reduced to a similar level as onshore terminals.

Table 3-6 Size of CO_2 buffer tanks and ships in Scenario 3 with the two alternative terminals (Note, the table data are only for the optimal shipping condition, "Opt cond").

Scenario	Route	CO_2 captured [m^3/d]	Sail [km]	Stops [-]	Round trip[a] [d]	Total buffer tank[b] [m^3]	Ship size [m^3]	Number of ships [-]
S.3	Ve+No+St+El	1999	632	3	4.0	8500[c]	8750	1
	Wa+Eq	1977	474	2	3.0	8000	6250	1
S.3 MN1 unloading 12 hours	Ve+No+St+El	1999	411	3	3.2	8500[c]	7500	1
	Wa+Eq	1977	337	2	2.6	8000	6250	1
S.3 MN1 unloading 36 hours	Ve+No+St+El	1999	411	3	4.3	8500[c]	10000	1
	Wa+Eq	1977	337	2	3.6	8250	7500	1
S.3 MN2 unloading 12 hours	Ve+No+St+El	1999	307	3	3.0	8250[c]	6250	1
	Wa+Eq	1977	224	2	2.2	6500	5000	1
S.3 MN2 unloading 36 hours	Ve+No+St+El	1999	307	3	4.0	8500[c]	8750	1
	Wa+Eq	1977	224	2	3.2	8250	7500	1

Ve=Verdalskalk, No=Norfrakalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.
[a] 12 hours of loading and 36 or 12 hours of unloading time. 14 knot ship speed.
[b] The tank size at each site is rounded-up to nearest 250 m^3.
[c] The tank size excludes 750 m^3 of buffer tank for trucks at Statkraft Varme Heimdal.

3.5 Low-pressure CO_2 shipping

Another approach to reducing the transport cost of Scenario 3 is the use of low-pressure CO_2 shipping, such as 7 barg instead of industrial standard 15 barg. There will be an increase in CO_2 conditioning and liquefaction costs since the liquefaction temperature will have to be reduced to about –50°C in the 7 barg case, compared to about -30°C in the 15 barg case. Still, the lower transport pressure is reported to decrease the CCS chain cost by up to 30% due to the large savings in the CO_2 transport part (buffer storage and marine shipping)[8].

This trend is also shown in the CCS Midt-Norge project. Figure 3-10 presents Scenario 3 with the CO_2 transport pressure of 7 barg and 15 barg for transport of CO_2 to the NL terminal. The 7 barg case has 37-42% lower transport costs compared to 15 barg although both cases have the same size and number of ships (see Table 3-7 for details). It is worth noting that the buffer tank size is slightly reduced when storing

---

[8] Roussanaly S, Deng H, Skaugen G, Gundersen T. At what Pressure Shall CO2 Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 Barg Shipping. Energies 2021;14:5635.

the same amount of captured CO_2 at 7 barg due to the higher density of liquid CO_2 at 7 barg (ca. 1150 kg/m^3 at -50 °C) compared to at 15 barg (ca. 1060 kg/m^3 at -30 °C).

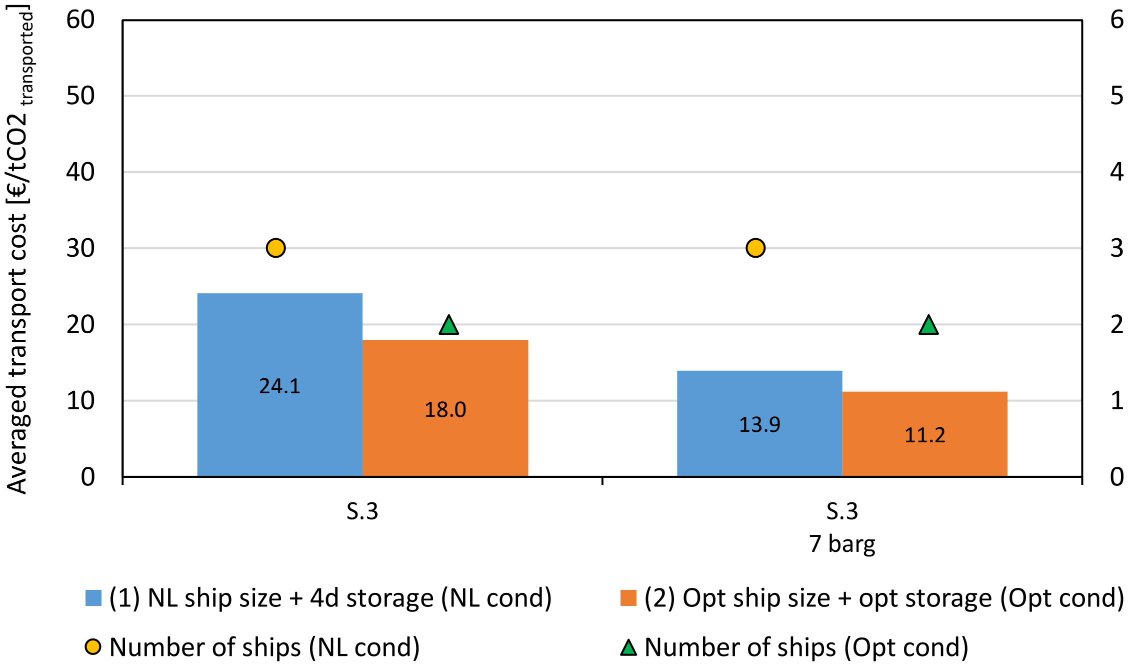

Figure 3-10 Options to reduce the transport cost of Scenario 3 to NL terminal: low-pressure CO_2 shipping.

Table 3-7 The size of the buffer tanks and the CO_2 ships in Scenario 3 with two different shipping pressure levels (15 barg and 7 barg) for transport to NL terminal using the optimal condition.

Condition	Route	CO_2 captured [m^3/d]	Sail [km]	Stops [-]	Round trip[a] [d]	Total buffer tank[b] [m^3]	Ship size [m^3]	Number of ships [-]
(2) Opt cond 15 barg	Ve+No+St+El	1999	632	3	4.0	8500[c]	8750	1
	Wa+Eq	1977	474	2	3.0	8000	6250	1
(2) Opt cond 7 barg	Ve+No+St+El	1840	632	3	4.0	8000[c]	8750	1
	Wa+Eq	1819	474	2	3.0	7500	6250	1

Ve=Verdalskalk, No=Norfrakalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.

[a] 12 hours of loading and 12 hours of unloading time. 14 knot ship speed.

[b] The tank size at each site is rounded-up to nearest 250 m^3.

[c] The tank size excludes 750 m^3 of buffer tank for trucks.

The main contributors to the cost cut for 7 barg transport are the reductions in the capital costs of the storage tanks and the CO_2 ships, which account for 50% of the total transport cost (see Table 3-8). The CAPEX of the 7 barg ship is almost half that of the 15 barg vessel, and the on-site buffer tank cost is reduced by 25%. The changes in the other ship cost items and the truck transport cost remain minor. Therefore, shipping liquid CO_2 at a low pressure appears to be a promising option to minimize the transport costs for the CCS Midt-Norge project, if the infrastructure and technology are available to be deployed in a timely manner.

Table 3-8 Breakdown of transport costs for Scenario 3 with 15 barg and 7 barg when using the optimal condition.

Condition	Route	Storage & Loading for ships		Ships				Ship transport cost	Truck Transport cost	Total Transport cost
		CAPEX	Fixed OPEX	CAPEX	Fixed OPEX	Fuel cost	Harbour fees			
		[€/tCO2$_{\text{transported}}$]								
(2) Opt cond 15 barg	Ve+No+St+El	1.2	0.6	8.6	4.5	1.4	1.1	17.4	3.6	21.1
	Wa+Eq	1.2	0.6	7.3	3.8	1.1	1.1	15.0	-	15.0
	Average	-	-	-	-	-	-	-	-	18.0
(2) Opt cond 7 barg	Ve+No+St+El	0.8	0.4	4.3	2.3	1.4	1.1	10.2	3.4	13.6
	Wa+Eq	0.8	0.4	3.6	1.9	1.1	1.1	8.7	-	8.7
	Average	-	-	-	-	-	-	-	-	11.2

Ve=Verdalskalk, No=Norfrakalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.

3.6 Main takeaways from the CO_2 logistics study

CO_2 logistics planning carried out for the CCS Midt-Norge project presents the following key findings[9], highlighting that cooperation between the industrial sites has a significant impact on the transport costs.

- Individual shipping routes give the highest CO_2 transport costs for all sites.
- Binding sites and sharing transport infrastructure leads to large cost savings.
- The Northern Lights CO_2 ship size and four days of buffer storage were found to be costly for the investigated scenarios.
- The size of the CO_2 ships and buffer tanks need to be selected based on the shipping plan.
- The optimal shipping plan is to minimize the number of ships with a reasonable round-trip time.
- Local offshore CO_2 terminals are not ideal due to long unloading time and thus longer round-trip time. However, if offshore unloading can be done as quickly as onshore, the transport costs can be slightly lower for the local terminals.
- Low pressure CO_2 shipping (7 barg) can reduce the transport cost by 35%, mainly due to the lower CAPEX cost of the ships.

---

[9] In the most recent base case for Equinor Tjeldbergodden, the value of captured CO_2 will be reduced from 718 m3/day to 638 m3/day. The most recent and lower CO_2 numbers are included in in Chapter 2 but was not known at the time of doing the logistics calculations here in Chapter 3. So, the value of 718 m^3/h has been used. However, for the most likely scenarios as evaluated here, Equinor and Wacker will share ship and have a total captured volume of 1977 m3/d. A reduction of just 80 m3/day of this number will not significantly alter the results from this study.

4 Non-technical CCS aspects and project communication actions

Insights into how logistics choices affect the cost of the CCS chain is one of the necessary elements for proceeding towards a second phase for the CCS Midt-Norge cluster, but it is not sufficient. Firstly, it is also important to gain insights into financial and other non-technical conditions that are of common interest in the cluster. Secondly, communication about the cluster with relevant local stakeholders is one of the cornerstones for building support and acceptance for CCS as a measure to reduce climate gas emissions. It is described in this section how these two aspects were addressed in the project.

4.1 Mapping financial and other non-technical conditions

In order to map the non-technical conditions that the partners in the CCS Midt-Norge cluster perceive as relevant for being able to actually realise CCS, interviews were made by SINTEF with the partners. The following questions were asked:

- What are the regulatory drivers for CO_2 capture/CCS/CCU implementation in your company/in your industrial sector?
- What do you need, to actually implement CO_2 capture/CCS/CCU?
- What are the opportunities for increasing the product selling price, to compensate for increased production cost?
- Have you identified relevant market mechanisms?
- What are the opportunities within the EU, including the Green taxonomy/access to green finance?
- What could your opportunities be for CO_2 use?
- Do you see any business opportunities that are specific for Mid-Norway?

Based on these interviews, a summary was made of the conditions where there is a general perception that this is of importance for the cluster. The paragraphs below present a map of the identified common financial and commercial conditions and frameworks for the development of CCS projects in Mid-Norway.

Regulatory drivers: The main regulatory drivers for implementing CO_2 capture are the EU-ETS and the Norwegian CO_2 tax. As the free quota under the ETS is reduced, the cost of emitting will increase, making it more convenient to capture CO_2 or use biogenic material than to emit.

Further drivers include the social/community benefit and the expectation that stricter emission regulations will be enacted in a few years, increasing both the emissions accounted for and the cost of emitting.

Needs for implementing CCS and CCU: Incentives, reasonable business models and the availability of clean energy are among the key needs for implementing CO_2 capture.
The state may contribute by developing incentives, support mechanisms and shared infrastructure for transport and intermediate storage, in addition to new projects which could increase the storage capacity offshore Norway. Development of transport and storage networks/hubs around the North Sea and solution for local transport and intermediate storage in Mid-Norway is crucial. Furthermore, a good and predictable economic framework has been highlighted as essential.

The CCU business model, although potentially profitable, is characterized by a large uncertainty with regards to the count of utilized CO_2 in the ETS, which prevents actors from investing in CO_2 utilization technologies. Here there is the need for a European framework for carbon removal, with common schemes for defining, certifying, and accounting the utilized CO_2.

Opportunities for increasing the product selling price: It is agreed that products will be more expensive if produced with CCS in the process.

Opportunities to increase the price to cover the costs of CCS may arise, but at present it is unsure if customers are willing to pay a premium for lower carbon footprint products.
The carbon border adjustment mechanism (CBAM) is expected to support companies who invest in low emission technologies, by introducing penalties towards carbon intensive producers. The correct design of such a scheme is pivotal to ensure a fair competitive landscape, and the opportunity to recover the extra product costs related to CCS.

Relevant market mechanisms: The EU-ETS market mechanism is the main driver for the deployment of CCS. Besides, different state support schemes for CCUS and carbon removal from bio-CCS in the form of reversed auctions, contracts for difference, and bilateral negotiations for investment support are expected. These mechanisms will probably differ by country.

Some companies see an interesting potential in the use of CO_2 over time, for instance by converting CO_2 to e-fuels[10]. The power needs to generate e-fuels come in addition to the power requirements for CCS. In this respect, the cost of power is currently an advantage for Mid-Norway.

Opportunities within the EU: CCS is sustainable under the guidelines outlined by the green taxonomy and qualifies for financial support of capital cost. Access to green finance, including better conditions on loans in reward for lower emissions or financing through, e.g. the SEB market (sustainability financing), are further opportunities. These schemes will primarily benefit companies listed on the stock exchange.

The EU Innovation Fund may be an additional supporting scheme for CCS. Connecting Europe Facilities (CEF) funding could possibly contribute to financing of common infrastructure, if there is a collaboration with Sweden (receiving CO_2 via train from Sweden to e.g. Muruvik).

Selling Carbon Removal Certificates for stored biogenic CO_2: On 30 November 2022, the EU presented a proposal for a Union certification framework for carbon removals[11]. The purpose is to establish a framework that enables selling carbon removal certificates e.g., to actors who wish to offset non-abatable emissions. The realisation of permanent carbon removals is an important building block to achieve the European goal of climate neutrality in 2050. The interest and market for carbon removals is growing and can represent important income for some of the partners, and thus contribute to necessary profitability. Statkraft Varme, Elkem and Wacker have a share of biogenic CO_2 in their flue gases, meaning that CCS for these industries would include realisation of carbon removals. Provided that Norway adheres to the certification framework for carbon removals, sale of carbon removal certificates could be part of a business model.

Opportunities for CO_2 use: CCU could partially offset the cost of CCS processes.
Using CO_2 on-site, especially if of biogenic origin, e.g., to develop biofuels or other chemicals, has been considered. There are requests to deliver CO_2 to multiple interested parties, such as algae production and fish farming.

---

[10] The terminology "e-fuels" is used for synthetic hydrocarbon fuels produced from CO_2 and H_2, where H_2 is produced through electrolysis of water.

[11] https://www.europarl.europa.eu/RegData/docs_autres_institutions/commission_europeenne/com/2022/0672/COM_COM(2022)0672_EN.pdf

Quick lime (produced by e.g., NorFraKalk) is used to produce PCC (precipitated calcium carbonate). This process binds most of the CO_2 (up to 93%) that is emitted from the limestone during the lime production process[12].

There is also a potential to bind CO_2 in the form of carbonates in building materials. Examples of companies in this area are Solidia, Carbon Cure, Neustark and Carbon8.

Business opportunities for Mid-Norway: CCS Mid-Norway has the advantage of the (current) electricity surplus in the region compared to the south of Norway. Production of electricity is also mainly from renewables in Mid-Norway, making for a secure market supply using the Norwegian energy mix. There could also be a potential for a CO_2 circularity hub in Mid-Norway, with local CO_2 management.

Key competitive advantages which can drive business opportunities in Mid-Norway include:
- High availability of renewable energy at a low cost.
- Important amounts of CO_2 from industrial point sources in proximity.
- Rather easy access to sea/ports.

These factors indicate a strong potential for competitive construction of hub infrastructure for CCS in the Mid-Norway region.

Project members have during the project had dialogue with local stakeholders, to contribute to anchoring CCS as measure to reach climate goals in municipalities and the region.

4.2 Communication about CCS Midt-Norge

Communication about the industrial cooperation in the CCS Midt-Norge cluster has been high on the agenda throughout the project. Project members have during the project had dialogue with local stakeholders, to contribute to anchoring CCS as measure to reach climate goals in municipalities and the region. These communication actions include presentations about the project to the following actors and fora:

- Trondheim Municipality
- Trondheim Harbour
- Orkland Municipality
- NRK (reportage on local TV + news article on nrk.no)
- Maritime forum in Trondheim
- CLIMIT Webinars for CCS clusters in Norway
- Mid-Norway Chamber of Commerce and Industry
- Mid-Norway climate and planning committee
- Mid-Norway European office in Brussels
- The Norwegian sea council (Norskehavsrådet)
- CLIMIT Summit
- Green Cargo

---

[12] Pietro Campo F., Tua, C., Biganzoli, L., Pantini, S., Grosso, M. Natural and enhanced carbonation of lime in its different applications: a review. Environmental technology reviews (2021) 10:1 224-237, DOI: 10.1080/21622515.2021.1982023

5 Realising CCS in Mid-Norway - what would it take?

There are today about 1.5 million tonnes of CO_2 emissions per year from the industries in the CCS Midt-Norge cluster. With 90% capture rate, almost 1.4 million tonnes CO_2 would be captured and need to be transported to a storage site.

For the transport of the captured CO_2 in the CCS Midt-Norge cluster, cooperation between the industrial sites for common CO_2 transport infrastructures is essential to minimize the logistics costs. Depending on the location and the level of emissions, the cost-optimal shipping routes can vary, and they require suitable ship and buffer tank sizes, which are often different from those considered for Northern Lights in the Longship project. As alternative solutions, low-pressure CO_2 transport is found to be promising, offering a cost reduction of more than 35% for the optimal shipping routes, while local offshore CO_2 terminals show marginal economic benefits due to the long offloading time. Thus, the potential of low-pressure shipping in CO_2 logistics needs to be further analysed to improve the economic viability of CCS in the CCS Midt-Norge cluster.

There is significant interest for cluster cooperations from authorities, ship owners and storage suppliers. This is due to the amount of CO_2 and the potential for shared solutions, which will enable scalable solutions with a potential to reduce cost for transport and permanent storage. Cooperation as a cluster will and strengthen the negotiation position with actors along the transport and storage chain.

All CCS projects will need some financial support to realize CCS in the medium term. It is expected that, from an authority's perspective, companies with mature projects and efficient value chains will be of prime interest. A cost-efficient solution for transport and storage is therefore important to establish.

In our case, Mid-Norway, there is an option to increase the volume of CO_2 to be stored through the inclusion of CO_2 from Sweden by train as well as from other large emission points in the region. Cooperateion with other clusters is a possibility–,for instance the CO_2 hub Nordland. This could lead to even more cost-efficient solutions.

Finally, there are challenges to be solved going forward meaning that evaluating utilization of captured CO_2 can represent and alternative or a supplement to permanent storage to improve the business model. This could be relevant either within the cluster as a solution for all, or for some of the partners.

Based on our findings in phase 1, the scope for a potential next phase of a cluster cooperation for management of captured CO_2 should therefore be to:

(i) further develop and decide on a preferred concept for transport and permanent storage,
(ii) solve challenges with different timelines for different industries regarding decisions and construction. In light of this, it must be addressed how to find a solution for legal framework/contracts, business models, financing and agreement(s) for permanent CO_2 storage,
(iii) analysis of different value chains, framework, actors/suppliers, markets, sustainability etc., for utilization of captured CO_2.

A Appendix – detailed results from the logistics study

Table A-1 Detailed CO_2 logistics of Scenario 1.

Case		Route	Transported CO2	CO2 captured	Ship						Truck/pipeline			Buffer storage distribution*** [m3]								Truck cost	Ship cost	Total cost
					Sail	Stops	Round trip	Buffer tank	Ship size	No. of ships	Length	Buffer tank	No. of trucks	Ve	No	St		El	Wa	Eq	Total			
			[Mt$_{CO2}$/y]	[m^3/d]	[km]	[-]	[d]	[m^3]	[m^3]	[-]	[km]	[m^3]	[-]	Site	Site	Site*	Port**	Site	Site	Site		[€/t$_{CO2transported}$]		
S.1	(1) NL	Verdalskalk	0.06	163	600	1	2.9	750	7500	1	-	-	-	750	-	-	-	-	-	-	750	0.0	154.7	154.7
		NorFraKalk	0.21	570	593	1	2.9	2500	7500	1	-	-	-	-	2500	-	-	-	-	-	2500	0.0	47.4	47.4
		Statkraft	0.22	560	533	1	2.7	2250	7500	1	31	750	6	-	-	750	2250	-	-	-	3000	12.6	46.2	58.7
		Elkem	0.26	705	532	1	2.7	3000	7500	1	-	-	-	-	-	-	-	3000	-	-	3000	0.0	39.0	39.0
		Wacker	0.49	1259	470	1	2.5	5250	7500	1	-	-	-	-	-	-	-	-	5250	-	5250	0.0	22.6	22.6
		Equinor	0.27	718	433	1	2.4	3000	7500	1	-	-	-	-	-	-	-	-	-	3000	3000	0.0	37.6	37.6
	(2) opt	Verdalskalk	0.06	163	600	1	2.9	750	1250	1	-	-	-	750	-	-	-	-	-	-	750	0.0	66.0	66.0
		NorFraKalk	0.21	570	593	1	2.9	2500	2500	1	-	-	-	-	2500	-	-	-	-	-	2500	0.0	29.2	29.2
		Statkraft	0.22	560	533	1	2.7	2500	2500	1	31	750	6	-	-	750	2250	-	-	-	3000	12.6	28.5	41.0
		Elkem	0.26	705	532	1	2.7	3000	2500	1	-	-	-	-	-	-	-	3000	-	-	3000	0.0	24.3	24.3
		Wacker	0.49	1259	470	1	2.5	4750	3750	1	-	-	-	-	-	-	-	-	4750	-	4750	0.0	17.1	17.1
		Equinor	0.27	718	433	1	2.4	3000	2500	1	-	-	-	-	-	-	-	-	-	3000	3000	0.0	23.4	23.4
	(1)	Avg. cost	1.50	-	-	-	-	-	-	6	-	-	-	-	-	-	-	-	-	-	17500	-	-	42.1
	(2)	Avg. cost	1.50	-	-	-	-	-	-	6	-	-	-	-	-	-	-	-	-	-	17000	-	-	26.6

Ve=Verdalskalk, No=Norfrakalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.
*Site storage for truck transport. **Storage tank on Orkanger port for truck unloading/ship loading. ***The tank size is rounded-up to nearest 250 m^3.

Table A-2 Detailed CO_2 logistics of Scenario 3 and its alternatives.

Case		Route	Transported CO2	CO2 captured	Ship						Truck/pipeline			Buffer storage distribution*** [m3]								Truck cost	Ship cost	Total cost
					Sail	Stops	Round trip	Buffer tank	Ship size	No. of ships	Length	Buffer tank	No. of trucks	Ve	No	St		El	Wa	Eq	Total			
			[Mt_{CO2}/y]	[m^3/d]	[km]	[-]	[d]	[m^3]	[m^3]	[-]	[km]	[m^3]	[-]	Site	Site	Site*	Port**	Site	Site	Site		[€/$t_{CO2transported}$]		
S.3	(1) NL	Ve+No+St+El	0.75	1999	632	3	4.0	8000	7500	2	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	28.6	32.3
		Wa+Eq	0.76	1977	474	2	3.0	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	16.0	16.0
	(2) opt	Ve+No+St+El	0.75	1999	632	3	4.0	8000	8750	1	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	17.4	21.1
		Wa+Eq	0.76	1977	474	2	3.0	8000	6250	1	-	-	-	-	-	-	-	-	5000	3000	8000	0.0	14.9	14.9
	(1)	Avg. cost	1.50	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	17500	-	-	24.1
	(2)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	17250	-	-	18.0
S.3 MN1 unload12h	(1) NL std	Ve+No+St+El	0.75	1999	411	3	3.3	8000	7500	1	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	16.0	19.6
		Wa+Eq	0.76	1977	337	2	2.6	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	15.7	15.7
	(2) opt	Ve+No+St+El	0.75	1999	411	3	3.3	8000	7500	1	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	16.0	19.6
		Wa+Eq	0.76	1977	337	2	2.6	8000	6250	1	-	-	-	-	-	-	-	-	5000	3000	8000	0.0	14.6	14.6
	(1)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	17500	-	-	17.6
	(2)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	17250	-	-	17.1
S.3 MN1 unload36h	(1) NL std	Ve+No+St+El	0.75	1999	411	3	4.3	8000	7500	2	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	28.1	31.8
		Wa+Eq	0.76	1977	337	2	3.6	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	15.7	15.7
	(2) opt	Ve+No+St+El	0.75	1999	411	3	4.3	8000	10000	1	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	17.5	21.1
		Wa+Eq	0.76	1977	337	2	3.6	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	15.7	15.7
	(1)	Avg. cost	1.50	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	17500	-	-	23.7
	(2)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	17500	-	-	18.4
S.3 MN2 unload12h	(1) NL std	Ve+No+St+El	0.75	1999	307	3	3.0	8000	7500	1	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	15.8	19.4
		Wa+Eq	0.76	1977	224	2	2.2	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	15.4	15.4
	(2) opt	Ve+No+St+El	0.75	1999	307	3	3.0	8000	6250	1	31	750	6	750	2250	750	2250	3000	-	-	9000	3.6	14.7	18.3
		Wa+Eq	0.76	1977	224	2	2.2	6250	5000	1	-	-	-	-	-	-	-	-	4000	2500	6500	0.0	12.9	12.9
	(1)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	17500	-	-	17.4
	(2)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	15500	-	-	15.6
S.3 MN2 unload36h	(1) NL std	Ve+No+St+El	0.75	1999	307	3	4.0	8000	7500	2	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	27.9	31.5
		Wa+Eq	0.76	1977	224	2	3.2	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	15.4	15.4
	(2) opt	Ve+No+St+El	0.75	1999	307	3	4.0	8000	8750	1	31	750	6	750	2500	750	2250	3000	-	-	9250	3.6	16.7	20.4
		Wa+Eq	0.76	1977	224	2	3.2	8000	7500	1	-	-	-	-	-	-	-	-	5250	3000	8250	0.0	15.4	15.4
	(1)	Avg. cost	1.50	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	17500	-	-	23.4
	(2)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	17500	-	-	17.9
S.3 7barg	(1) NL std	Ve+No+St+El	0.75	1840	632	3	4.0	7500	7500	2	31	750	6	750	2250	750	2250	2750	-	-	8750	3.4	15.8	19.2
		Wa+Eq	0.76	1819	474	2	3.0	7500	7500	1	-	-	-	-	-	-	-	-	4750	2750	7500	0.0	8.7	8.7
	(2) opt	Ve+No+St+El	0.75	1840	632	3	4.0	7500	8750	1	31	750	6	750	2250	750	2250	2750	-	-	8750	3.4	10.2	13.6
		Wa+Eq	0.76	1819	474	2	3.0	7500	6250	1	-	-	-	-	-	-	-	-	4750	2750	7500	0.0	8.7	8.7
	(1)	Avg. cost	1.50	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	16250	-	-	13.9
	(2)	Avg. cost	1.50	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	16250	-	-	11.2

Ve=Verdalskalk, No=Norfrakalk, St=Statkraft, El=Elkem, Wa=Wacker, Eq=Equinor.

*Site storage for truck transport. **Storage tank on Orkanger port for truck unloading/ship loading. ***The tank size of each site is rounded-up to nearest 250 m^3.