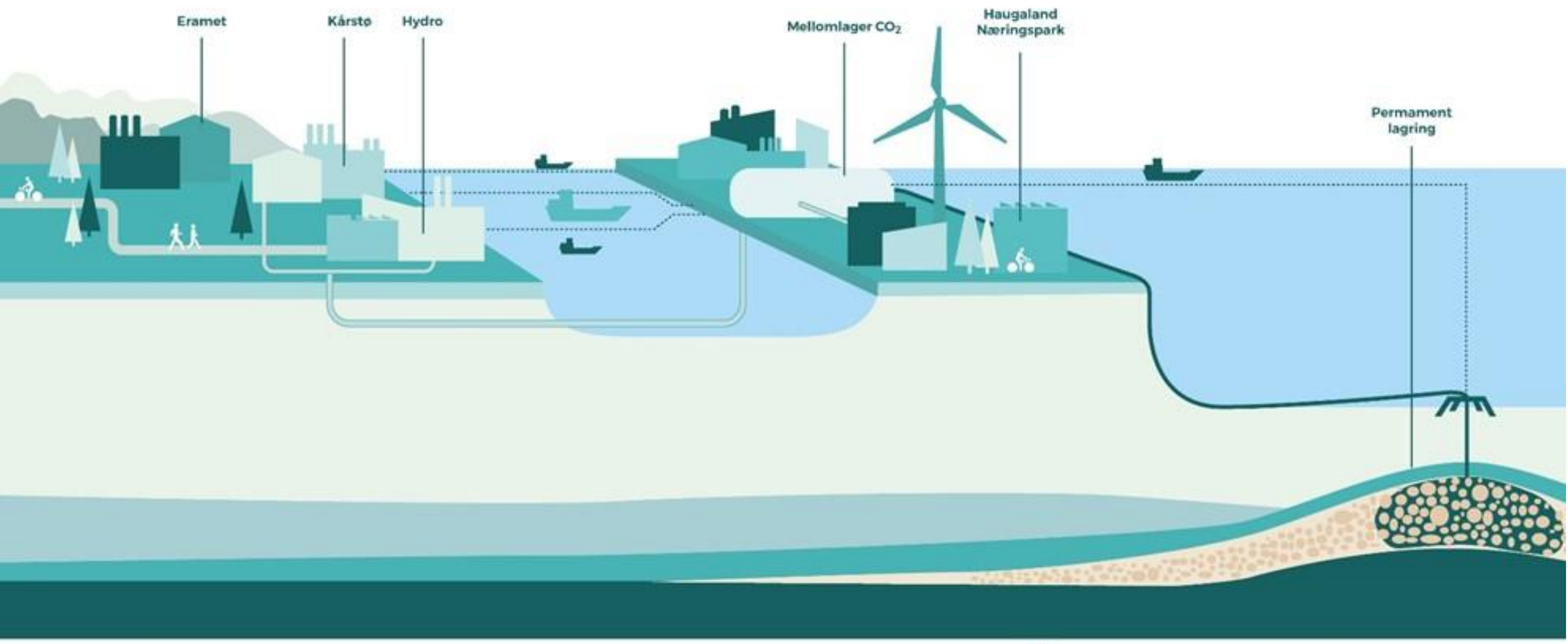
CCS HAUGALANDET



Report

CCS Haugalandet

Evaluation of CO2 logistics scenarios in the Haugalandet region

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Clients:

Haugaland Næringspark, Eramet Norway Sauda, Equinor, Gassco, Hydro Aluminium, Gassnova

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Report

CCS Haugalandet

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SUMMARY
Eramet Norway Sauda, Hydro, Gassco/Equinor and Haugaland Næringspark (HNP) have joined forces in a CCS cluster to evaluate benefits from cooperating on transport of captured CO_2 to a storage terminal. Total CO_2 emissions in the cluster were in 2022 1.5 million tonnes, which can be expected to increase as novel industries are being established at HNP. Four logistics options were evaluated with the SINTEF Energy iCCS tool for two different sets of daily captured CO_2 volumes and two different shipping conditions (Northern Lights and optimised conditions). The results confirm that cooperation gives cost savings and show that the optimal logistics solution varies, depending on amount of CO_2 transported. Impact of distance to CO_2 storage terminal on cost was investigated as well as the impact on cost when reducing ship transport pressure from 15 barg to 7 barg. Minimising CO_2 transport cost is only one part of a cost-efficient CCS chain. Access to CO_2 storage at a reasonable cost is necessary for realising a CCS business models for industry.

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SINTEF

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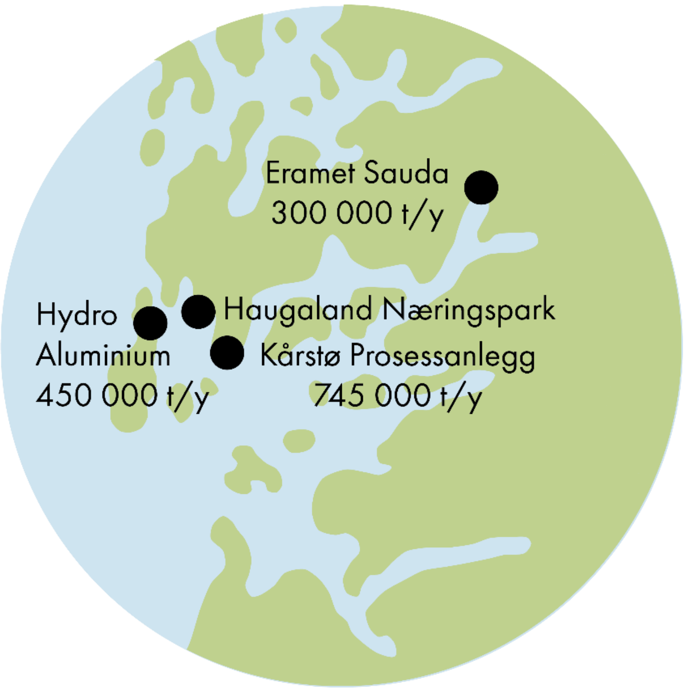
Executive summary

The Norwegian Environment Agency (MDIR) has identified CCS as the measure with the largest potential for achieving emission cuts in Norwegian industry and energy supply towards 2030-2035[1]. To realise this, cost-efficient CO_2 capture, transport and storage is required.

The combined CO_2 emissions from Eramet Sauda Norway, Hydro Aluminium Karmøy, and the Gassco/Equinor gas processing plant at Kårstø, were 1.5 million tonnes in 2022. The Haugalandet Næringspark is Norway's largest industrial park with zoning, with upcoming establishment of industrial actors, and is planning to host a CO_2 storage terminal.

These industrial actors have joined forces in the *CCS Haugalandet* project with the aim to evaluate the benefits of cooperating as an industrial CCS cluster. The results presented in this report confirm the initial assumption, that there are indeed cost benefits from collaborating on solutions for transport of captured CO_2 to storage.

Cutting costs only in CO_2 transport, is insufficient for industries to build viable CCS business models. Cost-efficient CO_2 capture is not a part of this study but addressed by the industries in individual projects kept outside the cluster cooperation. CO_2 delivery to a storage terminal, on the other side, is of joint interest. During the project, the cluster members have received signals that their relatively small CO_2 volumes may not be compatible with the business models established by transport and storage operators. Cooperation with authorities and initiatives on a national level are important to ensure that Norwegian CO_2-emitting industries get access to cost-efficient transport and storage solutions.



Industrial sites in the Haugalandet CCS cluster, including annual CO_2 emissions in 2022.

[1] https://www.miljodirektoratet.no/publikasjoner/2023/juni-2023/klimatiltak-i-norge-mot-2030/

1 About the Haugalandet CCS cluster and the industry partners

1.1 The Haugalandet CCS cluster

The Haugalandet region located on the south-western Norwegian coast, is well situated for delivering captured CO_2 for storage on the Norwegian Continental Shelf (NCS). There are three major industrial actors in the region, with current total annual emissions of around 1.5 million tonnes CO_2: Hydro Aluminium Karmøy, Gassco/Equinor at Kårstø and Eramet Norway in Sauda. In addition, the Haugaland Næringspark (HNP) is Norway´s largest zoned industrial park, with high ambitions for hosting new, green industries. HNP has an agreement with Horisont Energi for establishing a CO_2 terminal at their harbour, which will provide easy access to CO_2 transport and storage for these new industries.

The proximity to CO_2 storage opportunities, the presence of CO_2-emitting industries, the plans for a CO_2 terminal, and the prospects for new industrial establishment that will further increase CO_2 emissions, makes it highly relevant to investigate what the benefits could be for industrial actors to cooperate as an industrial CCS cluster. This would mean to realise common infrastructure and plans for cost-efficient CO_2 transport to permanent storage. Such cluster cooperation could potentially further increase the attractiveness for new energy-intensive industrial establishments in the region. A common CO_2 infrastructure could comprise elements such as common ship transport, intermediate CO_2 storage and pipelines between industries and/or to a permanent storage site[2].

Based on this, the Haugalandet CCS cluster project was established, with support from the industrial partners and Gassnova (CLIMIT Demo project no. 622125). Project duration has been January 2023-January 2024. The project has defined different CO_2 transport scenarios and conditions relevant to the cluster. Thereafter, simulations to evaluate the scenarios were made with the SINTEF Energy iCCS tool. The main results are summarised and analysed in this report.

The report also includes a brief summary of stakeholder outreach activities and emphasizes the need for Norwegian industries to obtain access to CO_2 storage at a reasonable cost, to be able to contribute to national goals for emission cuts.

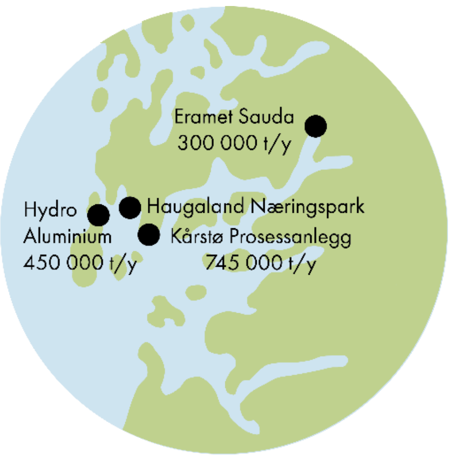


Figure 1-1: Industrial sites in the Haugalandet CCS cluster, including annual CO_2 emissions in 2022.

[2] A previous study for Mid-Norway was presented by Jordal K, Langørgen Ø, Kim D, Finotti F, Roussanaly S, Marsh N, Voldsund M: The CCS Midt-Norge cluster: industrial CCS collaboration for exploring synergies and common interests. SINTEF Energy Research 2023. https://www.sintef.no/globalassets/sintef-energi/pdf/ccs-midt-norge-final-report-v1.0---signert.pdf

1.2 Eramet Norway Sauda

Eramet Norway Sauda is the largest ferro manganese alloy producer in northern Europe. Three products are produced - high carbon ferro manganese alloy, medium and low carbon refined ferro-manganese alloy and manganese slag from the production. The raw material is manganese ore delivered by ship from Gabon. The plant is located in Sauda in Rogaland and the products are exported mainly to Europe and North America. The plant has 166 employees, and it is a cornerstone company in the Sauda municipality.

Eramet Sauda has two 40 MW_{el} smelter furnaces where the manganese ore is reduced to manganese with coke and anthracite as reducing agents. The flue gases from the furnaces consist of CO, CO_2, H_2, O_2 and N_2 with a CO concentration that varies between 45-90%[3]. Currently, most of the gas is flared to burn out the CO and H_2 to CO_2 and H_2O. The flue gas from the furnaces is the main source of CO_2 from the plant. In 2022, Eramet Sauda emitted 300 000 tonnes of CO_2[4].

The heating value of the furnace flue gas before being flared, amounts to around 40 MW_{th} for the two furnaces together, due to the CO and H_2 content. A smaller scale energy recovery system has been implemented where some of the furnace flue gas is burnt in a gas engine producing 1.5-1.7 MW_{el}. Additionally, the engine also provides approximately 2.0-2.5 MW_{th} hot water which is sent to Sauda for district heating. There are plans to install six more of these gas engines, a project that recently was granted support by ENOVA[5]. With a total of seven engines, the power production capacity will be about 12 MW_{el} and annual energy production approximately 90 GWh_{el} and 150 GWh_{th}[6], which equals the power and energy consumption of the planned CO_2 capture facility. After the installation of the new gas engines, most of the flue gas will be burned in these. This is a preparation for CO_2 capture as it maximizes the amount of CO_2 that can be captured since the CO is burned in the gas engines instead of being flared. The CO_2 concentration in the exhaust streams will be between 22-28% after the gas engines.

In parallel, a CO_2 capture pilot project was granted[7]. The technology to be demonstrated is Pressure Swing Adsorption (PSA), which has a high potential for efficient CO_2 capture at a CO_2 concentration above 15%. The pilot is foreseen to capture around 150 kg CO_2/hour and will be operated for approximately one year. For its full-scale capture, Eramet Sauda plans to install a PSA unit together with a liquefaction process downstream of the gas engines. The CO_2 will be liquified to 15 barg and -26.6°C, matching the standard conditions for ship transport of CO_2.

The full-scale capture plant is planned to start operating in 2028, reaching full operational capacity in 2030. The electrical consumption of the capture plant will be offset by the gas engine power production. The captured CO_2 at Sauda can be exported by ship. Sauda has two quays, one used to receive the raw materials and one used to ship the products (cf. Figure 1-2). Due to space requirements for the needed capture infrastructure and equipment, the receiving quay is foreseen to be used for CO_2 export.

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[3] Kero, I.T., Eidem, P.A., Ma, Y. et al. Airborne Emissions from Mn Ferroalloy Production. JOM 71, 349–365 (2019). https://doi.org/10.1007/s11837-018-3165-9

[4] Miljødirektoratet, 'Norske Utslipp, Eramet Norway Sauda.

[5] https://www.enova.no/om-enova/om-organisasjonen/teknologiporteføljen/gjennvinning-av-energi-fra-ovnsgass-ved-eramet-norway-sauda-as/

[6] https://kommunikasjon.ntb.no/pressemelding/eramet-norway-far-132-millioner-kroner-til-energi--og-klimaprosjekter-i-sauda?publisherId=17848299&releaseId=17961810

[7] https://www.enova.no/om-enova/om-organisasjonen/teknologiporteføljen/planlegging-installasjon-og-drift-av-karbonfangst-pilotanlegg-i-eramet-norway-sauda/

Eramet Sauda has one of the lowest CO_2 footprints for ferro manganese production worldwide with 1.4 tonne CO_2 per tonne refined product. Green alloy demand is on the rise, notably in the steel industry. In the future, if the demand for green alloys increases significantly, it can help to make the business case for CO_2 capture more competitive. Additionally, Eramet Sauda has plans for replacing up to 40% of the fossil coal used for reduction with biochar. When combined with the implementation of CO_2 capture, the biogenic CO_2 stemming from the biochar will provide Carbon Dioxide Removal (CDR).

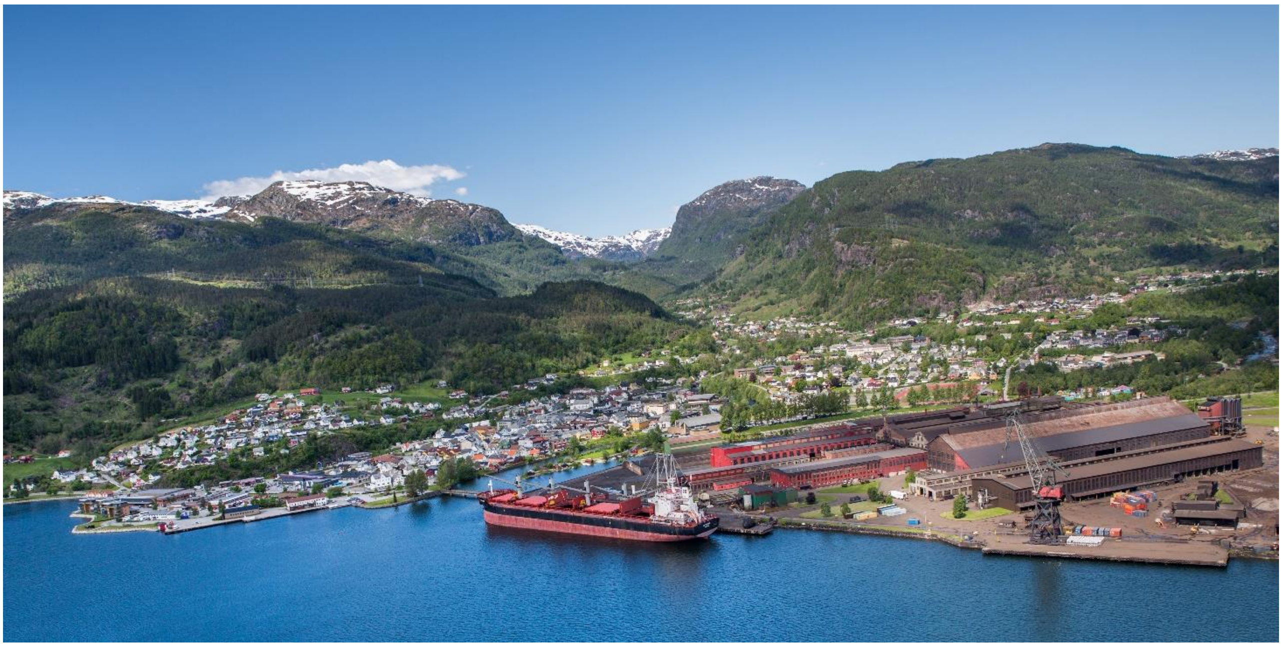

Figure 1-2: Location of Eramet Sauda next to Sauda municipality, and with the two quays for offloading raw materials and loading products. Photo: Eramet Norway.

1.3 Gassco/Equinor Kårstø

Gassco/Equinor Kårstø gas processing plant is located at Kårstø in Rogaland, south-east of Haugesund. It began operations in 1985. The processing plant plays a key role in transport and treatment of gas and condensate from central parts of the Norwegian Continental Shelf (NCS) and it is the largest of its kind in Europe. The plant employs about 1100 person-years, of which 400 are from hired vendors. Equinor is the technical service provider to the operator Gassco.

The plant separates rich gas, arriving through the Statpipe and Åsgard transport pipelines, into its various components. About 90 million Sm^3 rich gas can be processed each day. The dry gas product, mainly methane, is exported from Kårstø by pipelines while natural gas liquids (NGL) and condensate are exported by ship[8]. Kårstø has a production capacity of about 10 million tonnes natural gas liquids and condensate per year.

In 2022, the plant emitted approximately 745 000 tonnes CO_2 which is a significant decrease from the peak of 1 206 000 tonnes/year in 2017[9]. The CO_2 mainly comes from gas streams used as fuel for turbine-driven

[8] https://gassco.eu/prosessanlegg/karsto/
[9] https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=6428

compressors and for steam boilers. Compression of sales gas and steam for the fractionation processes represent more than 50% of the energy demand at Kårstø. There are large seasonal variations in gas processing at Kårstø and thus also in the CO_2 emissions. Within each of the two 6-month seasons, the emissions of CO_2 can be assumed to be constant.

Two scenarios for CO_2 capture have been investigated as possible at Kårstø:

1) 150 000 - 200 000 tonne/year CO_2. This is captured from an ethane-rich gas stream with a CO_2 concentration of more than 50%. With this high concentration, the CO_2 separation should have a fairly low energy consumption compared to many other industrial flue gases.
2) 400 000 - 500 000 tonne/year CO_2. This scenario includes the CO_2 from scenario 1 plus more CO_2 from another process unit, resulting in a CO_2 concentration of 3.5 - 5 % before capture.

A solvent-based technology using an amine for CO_2 absorption is being considered as the base case for CO_2 capture.

There is sufficient space on site for installation of a CO_2 capture plant and intermediate CO_2 storage. There is also space and operational flexibility at the piers for installing the additional equipment necessary for CO_2 export by ship.

For the logistics studies in this project, it is assumed that the CO_2 will be liquefied on site to conditions suitable for ship transport (liquid at pressure 15 barg) or compressed to dense phase for pipeline transport at about 110 barg pressure.

Figure 1-3: Overview of the Kårstø gas processing plant. Photo Markus Johansson /©Equinor.

1.4 Hydro Aluminium Karmøy

The Hydro Aluminium plant at Karmøy is one of Europe's largest aluminium plants and produces 270 000 tonnes of primary aluminium and 220 000 tonnes of cast aluminium annually. The plant has been in operation since 1967[10] and has 520 employees. Of the primary aluminium produced, 75 000 tonnes/year is produced in the technology pilot plant started in 2018. This pilot has shown stable and excellent performance, and produces the world's most climate- and energy-efficient primary aluminium.

The aluminium is produced using the Hall-Héroult process, where alumina (Al_2O_3) is reduced to aluminium in an electrolysis process. The carbon required for the reduction is supplied by carbon anodes, meaning that CO_2 emissions from the process are an inherent part of the aluminium production. CO_2 emissions from Al_2O_3 reduction amounts to approximately 1.5 tonne of CO_2 per tonne of aluminium produced. The main energy source for the primary metal production at Karmøy is renewable electric power.

The CO_2 emissions from Hydro Karmøy were 449 000 tonnes in 2022. With 24 h/day operation for 365 days/year, this gives CO_2 emissions of around 1200 tonnes/day when the plant is in full operation. The operation at Hydro Karmøy is a steady state process and is stable over the year with only minor variations in power consumption and CO_2 emissions. The CO_2 concentration in the flue gases is typically very low, roughly around 1%, which is normal for such electrolysis emissions.

Hydro is committed to achieving net-zero emissions by 2050 or earlier and the ambition is to take the lead in delivering zero-carbon aluminium by 2030. To deliver on this ambition, there is a need for new technologies that enable net-zero products and achieve net-zero operations. One of Hydro's main pathways to net-zero aluminium production, is capturing CO_2 from off-gases at existing smelters. Hydro is on track to deliver the first CO_2 capture in 2024 and industrial-scale pilot volumes by 2030.

For the logistics studies in this project, it is assumed that the captured CO_2 will be conditioned onsite either to liquid at pressure 15 barg suitable for ship transport or compressed to dense phase for pipeline transport at about 110 barg.

Figure 1-4: The Hydro Aluminium production plant at Karmøy. Copyright Hydro.

[10] Karmøy Primary Production (hydro.com)

1.5 Haugaland Næringspark

Haugaland Næringspark (HNP) is Norway's largest zoned business park with its own port facility and deep-water quays for efficient logistics. The park is located at Gismarvik in the municipality of Tysvær in Rogaland. The business park is owned by the municipalities of Karmøy, Haugesund, Tysvær, Vindafjord, and Bokn. The region is welcoming new businesses.

The business park itself will house an important energy hub on the west coast of Norway. Statnett's new 420 kV transformation station at Gismarvik is planned to be in production Q4 2027. The station will be located in the business park. Statnett's further plans for the grid will give a capacity of 3400 MW in the Haugalandet region[11]. There is already a wind power plant established in the business park and there are also plans for a solar plant in the park.

Clean energy and large zoned aeras attract large scale industries like battery, CCS, hydrogen, biofuel, biocarbon, data center, and process industry.

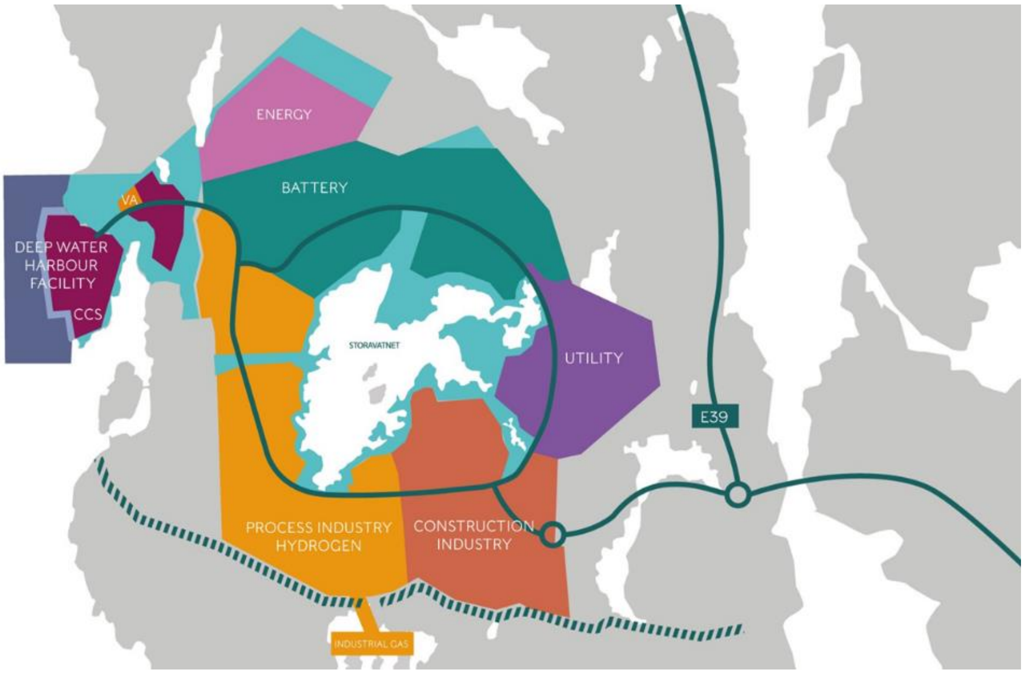

Figure 1-5. Example of businesses within the zoned area of Haugaland Næringspark. Illustration: Haugaland Næringspark

There are 19 companies established in the business park today. With Horisont Energi´s planned CO_2 terminal at the harbour, the business park will be a natural hub for CCS in the Haugalandet region. This, together with clean hydropower and 5000 decare (1234 acres) zoned area, makes the business park an attractive and relevant location for production of i.e., blue hydrogen and the steel industry.

[11] *(https://www.statnett.no/vare-prosjekter/region-vest/sauda-gismarvik/nyheter-fra-prosjektet/statnett-slar-sammen-to-ledningsprosjekter-pa-haugalandet/)*

In the portfolio of companies that want to establish their business in the park, there are large energy streams of both excess heat and cooling identified. There are strong ambitions for industrial symbiosis and for making it possible to utilize these energy streams in the park.

New establishments will cause a stepwise increase in CO_2 emissions, and it is currently not possible to pin the amount. The quality of CO_2 can be diverse, since each company will have their own industrial process and emissions can be both fossil and biogenic.

Most companies considering establishment at Haugaland Næringspark are interested in the opportunity to transport and store their CO_2. There are early phase plans for common CO_2 transport infrastructure from the different plants in the park, to the CO_2 terminal at the harbour. Gas pipes for low pressure gas are established in the main road, and these could be relevant also for transporting the CO_2 internally. Haugaland Næringspark has a deep-water quay, suitable for large-scale ship transport of CO_2. Horisont Energi's planned CO_2 terminal will be located close to this quay, on the right-hand side of the harbour shown in Figure 1-5. The terminal has a planned yearly capacity of 24 million tonnes CO_2.

It is strategically important to establish infrastructure connected to permanent storage of CO_2 in the business park. With a CO_2 terminal, excess green power, water, efficient logistics, and zoning, Haugaland Næringspark will be a one-stop-shop for low- and zero carbon industries.

Figure 1-6: Overview of Haugaland Næringspark and the harbour where a CO_2 terminal is planned. Photo: Haugaland Næringspark

1.6 CO_2 volumes in the logistics study

For each of the industrial sites in the Haugalandet CCS cluster, two different volumes of captured CO_2 (small and large volumes) were defined for use in the logistics study, as shown in Table 1-1. These CO_2

volumes are preliminary values for the industries in the CCS Haugalandet cluster. Using two different values for each site provides an insight into how logistics costs may vary, depending on the CO_2 volumes, and provides first insights in potential changes over time, reflecting that CO_2 capture implementation may be done in a stepwise manner among the cluster members. The small CO_2 volumes provided in Table 1-1 are intentionally different between Hydro and Gassco. This is to provide a variety in the results and increase the insights from the logistics study, given that the sailing distances to Northern Lights are quite similar for Hydro, Gassco (and HNP). In other words, the small volumes should not be seen as representing concrete plans.

Table 1-1: Amount of CO_2 captured, used as design values for the logistics study.

	Unit	Eramet	Gassco	Hydro	HNP	SUM
CO_2 captured per day (Small volumes)	t/d	480	600	300	1 235	2 615
CO_2 captured per day (Large volumes)	t/d	760	1 645	940	3 150	6 495

2 CO_2 logistics scenarios and shipping conditions

2.1 Logistics scenarios

CO_2 logistics scenarios were defined jointly by the cluster project partners, aiming to find cost-effective CO_2 transport solutions for four industrial sites in the Haugalandet region. The Northern Lights (NL) CO_2 terminal was for the purpose of this study considered as the storage destination in all scenarios but one, as it is currently the only CO_2 terminal under construction in Norway. The location of the NL terminal in relation to the Haugalandet CCS cluster is shown in Figure 2-1. It should be noted that other potential storage sites in the area will be evaluated, as these and the industrial capture projects in the cluster mature, and the sailing distance´s effect on the transport cost has therefore been investigated. In particular, it is of interest to the CCS Haugalandet cluster that HNP has an agreement with Horisont Energi to establish a CO_2 terminal. Scenario 3 in the logistics study, therefore, considers CO_2 delivery to HNP, for further transport by pipeline to a storage site on the NCS. The cost for pipeline transport from terminals to final storage is not included in the study, neither for Northern Lights north of HNP. The routes for different scenarios are described in Table 2-1 together with scenario sailing distances in Nautic Miles (NM).

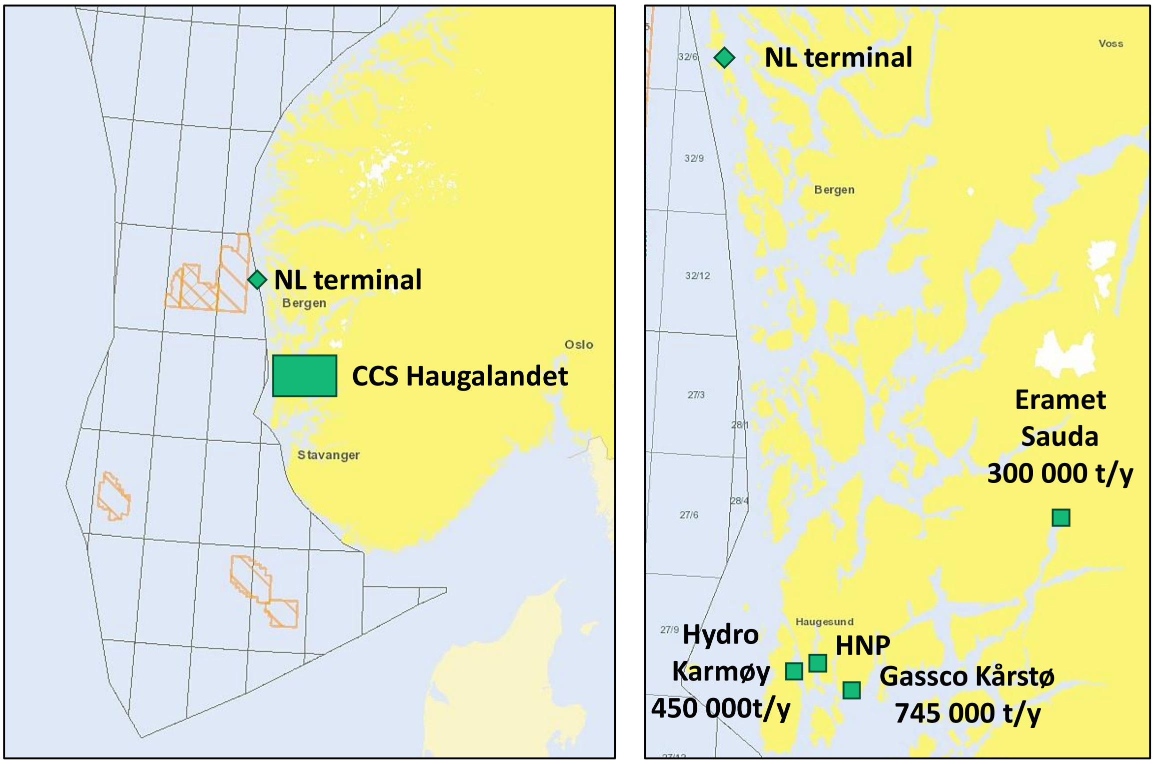

Figure 2-1: Location of the Northern Lights (NL) CO_2 terminal, the industries in the CCS Haugalandet cluster and CO_2 storage licences in the vicinity of Haugalandet (areas with orange border on the left figure). The map is adopted from https://factmaps.sodir.no/factmaps.

Table 2-1. *Logistics scenarios for the CCS Haugalandet cluster project.*

Scenario	Transport solutions	Saling distance [NM]
Scenario 0 no cluster collaboration	Eramet (ship) NL terminal Gassco (ship) NL terminal Hydro (ship) NL terminal [HNP (pipeline) HNP port] (ship) NL terminal	134 94 83 95
Scenario 1 without HNP	Eramet (ship) Gassco (ship) Hydro (ship) NL terminal	137
Scenario 1	Eramet (ship) Gassco (ship) Hydro (ship) [HNP (pipeline) HNP port] (ship) NL terminal	146
Scenario 2	Eramet (ship), Gassco (pipeline), Hydro (pipeline), HNP (pipeline) → HNP port (ship) NL-terminal	145
Scenario 3 terminal at HNP port	Eramet (ship), Gassco (pipeline), Hydro (pipeline), HNP (pipeline) → HNP port and terminal	52

Scenario 0 is the baseline where there is no cluster cooperation. In this scenario, each industrial site has its own ship and separate shipping transport route to the Northern Lights terminal. This typically results in high costs due to the large number of CO_2 ships in total. Haugaland Næringspark (HNP) uses a pipeline to transport CO_2 captured from a future industry location in the park to the HNP port, and thereafter uses a ship to deliver the CO_2 to the NL terminal.

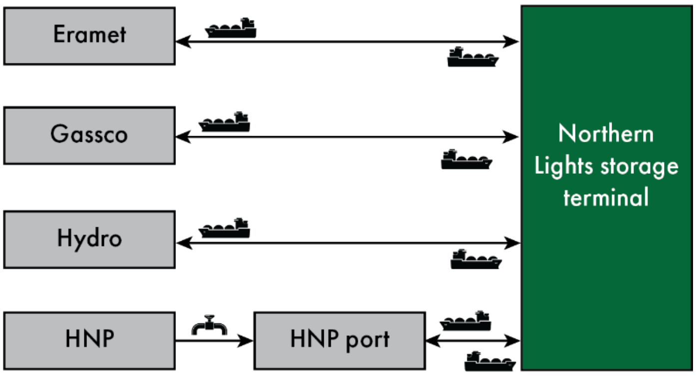

Figure 2-2. *Scenario 0. No cluster cooperation.*

Scenario 1 proposes a shared ship-based transport infrastructure connecting all the industrial sites via one common shipping route before delivering CO_2 to the NL terminal. The logistics are simplified, but Scenario 1 also has a longer voyage time compared to Scenario 0 due to the increased number of stops and total loading time before reaching the Northern Lights terminal. Two alternatives were investigated: one including CO_2 delivery from HNP to the common ship route (Scenario 1) and one without (Scenario 1 without HNP), in which case HNP would maintain its individual ship transport route calculated in Scenario 0. The reason for including this alternative is to investigate if the substantial CO_2 volume from HNP means that it is beneficial to maintain the standalone case.

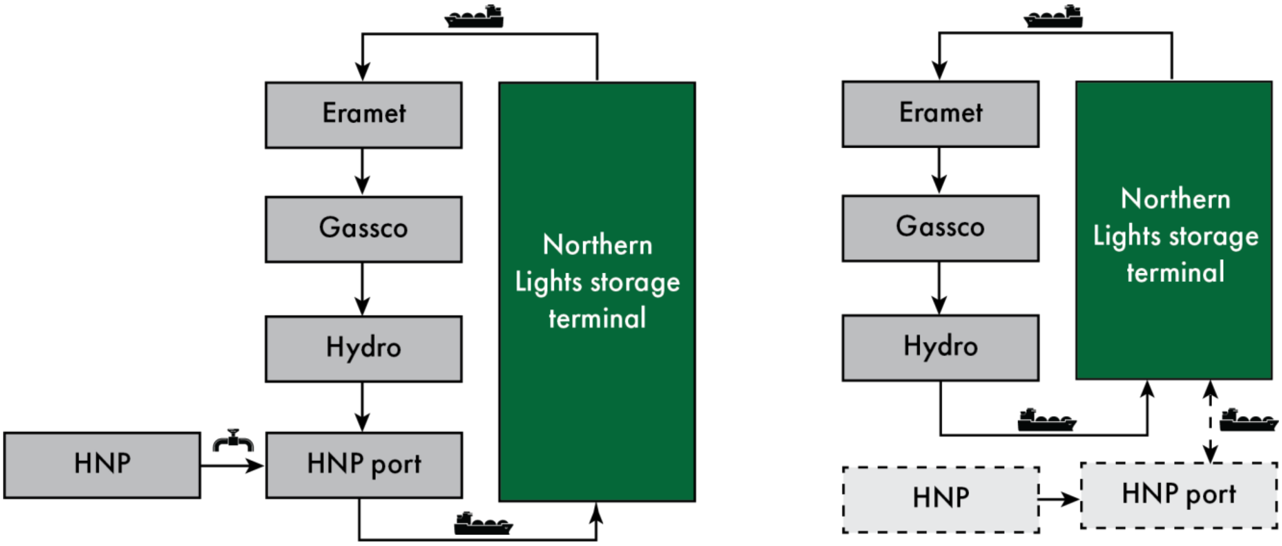

Figure 2-3. Scenario 1. A common ship route for all cluster partners (left) or a common ship route for all without HNP (right).

In *Scenario 2*, pipeline transport from three of the industrial sites is included, to reduce the number of ports visited and the total sailing time compared to Scenario 1. A pipeline connection to the HNP port is relevant for Gassco and Hydro due to the proximity. The piping was routed based on input from the industries of already existing, regulated infrastructure routes between the sites. Eramet will still use ship transport in Scenario 2, considering the long pipeline distance from Sauda to the HNP port. Consequently, Scenario 2 has only two stops for the ship, at Eramet and at the HNP port, reducing the total sailing time to the NL terminal compared to Scenario 1. Thus, the economic viability of Scenario 2 depends on the additional pipeline costs.

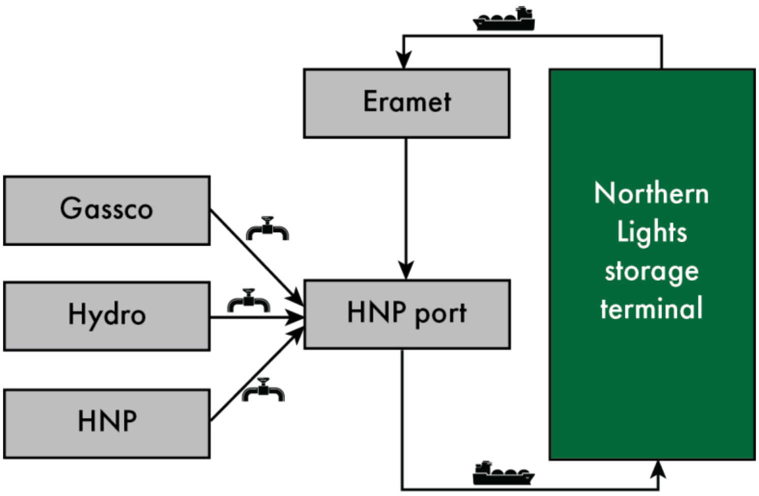

Figure 2-4. Scenario 2. Pipeline to HNP port for all industries except Eramet, CO_2 delivery by ship to Northern Lights terminal.

Scenario 3 builds on Scenario 2 but assumes that a CO_2 terminal is available at the HNP port. Similar to the Northern Lights terminal, CO_2 from the HNP terminal would be transported through a pipeline to an offshore storage site. This solution would allow for CO_2 from Gassco, Hydro, and HNP to be transported by pipeline only, without the need for CO_2 liquefaction or buffer tanks. Consequently, this scenario involves only a short shipping route between Eramet and the HNP port, reducing costs compared to other scenarios. However, the investment decision for the alternative CO_2 terminal has not yet been made and there is also uncertainty regarding the permanent storage cost.

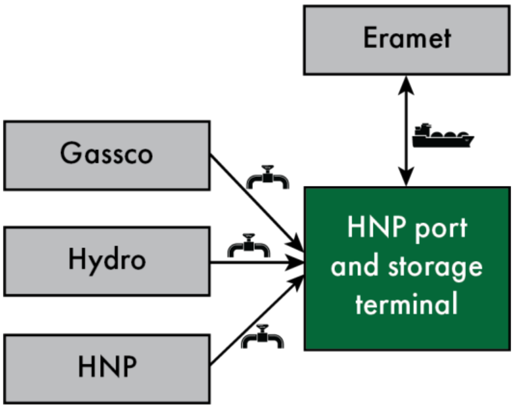

Figure 2-5. Scenario 3. Pipeline to HNP port for all industries except Eramet. CO_2 terminal at HNP.

Two *Scenario variations* were made for the most economical ship transport routes: 1) Investigation of the impact of varying the transport distance to the CO_2 terminal. 2) Low-pressure shipping, to evaluate the cost reduction potential[12].

2.2 CO_2 shipping conditions and economic performance

Shipping of liquid CO_2 at industrial standard pressure (15 barg) is used as the default transport mode. Based on the information from the industry partners, it is assumed that existing quay infrastructure can be used for the CO_2 ships. Pipeline CO_2 transport is assumed to be carried out in a dense phase at 110 bara from Hydro and Gassco and inside HNP to the HNP port.

Truck transport is excluded from the study due to the very large number of trucks needed to handle the given volumes, and in the case of Eramet also due to the distance and the road conditions.

As shown in Table 2-2, two different CO_2 shipping conditions were investigated. 1) The Northern Lights fixed ship size and four-day buffer storage at the quay, which represents the approach used for the sites in the Northern Lights project (Norcem Brevik and Hafslund Oslo Celsio). 2) The optimal condition, exploring ship sizes from 1 250 to 10 000 m^3 with two different approaches for defining the buffer tank size.

The economic performance of the logistic scenarios was evaluated with the SINTEF Energy iCCS tool[12] under two different sets of CO_2 volumes (see Table 1-1) for the NL shipping condition, while identifying the optimal ship and buffer tank sizes that provide the lowest cost (optimal shipping condition).

[12] Roussanaly S, Deng H, Skaugen G, Gundersen T. At what Pressure Shall CO_2 Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 Barg Shipping. Energies 2021;14:5635.

Table 2-2: The two investigated shipping conditions for the CO_2 logistics study.

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

As expected, the optimal condition was found to have lower costs than the Northern Lights condition in all investigated scenarios. To illustrate this, the results of the Northern Lights condition are presented for Scenario 0. This also shows that the cost difference between the Northern Lights and the optimal shipping condition will vary, depending on factors such as the amount of CO_2 transported and the sailing distance.

3 Results

In this chapter, the normalised transport cost per tonne of CO_2 for the investigated logistic scenarios is presented based on the results obtained with the iCCS tool[12]. The cost for the most expensive case has been set to 100. This is the case with Northern Lights shipping condition with small CO_2 volumes for Hydro in Scenario 0, where each site has its own ship. The reason why the cost for the Hydro case is the highest, is that this represents smallest low CO_2 volume in Table 1-1, while the CO_2 ship size is relatively large (NL ship: 7 500 m^3). As mentioned in Section 1.6, the low volumes for Hydro and Gassco should not be seen as representing concrete plans for these industries but were intentionally made different to increase the insights from the logistics study. With the normalised cost for the low-volume Hydro case as a starting point, it is possible to use scenario-based calculations to identify the relative impact of different factors, such as increased CO_2 volumes, optimised shipping conditions, shared ships, pipeline transport and delivery of CO_2 to a prospective HNP CO_2 terminal, rather than the NL terminal. Calculated transport costs in the different investigated logistic scenarios are based on the estimated daily amount of CO_2 captured at each site, as listed in Table 1-1, meaning that all scenarios were studied for both the small and large volumes of CO_2 provided in this table.

3.1 Scenario results

3.1.1 Scenario 0: no logistics collaboration

Results of Scenario 0 for the small CO_2 volumes are shown in Figure 3-1 and provide the baseline against which other results are compared. One can see that the individual shipping costs vary between the industries in a manner that is almost inversely proportional to the annual ship utilization rate. The low annual ship utilization rate under the NL shipping condition, means that the average filling rate of the fleet cargo capacity over a year is low, giving poor usage of the ships. Instead, optimising the ship size and buffer tank capacity (optimal shipping condition cases) increases the ship utilization rate and cuts the ship cost per transported unit mass of CO_2 (ship CAPEX and ship annual fixed OPEX), which is the main cost driver for the logistic cost. The reduction in cost for the individual industries varies, but it can be seen that the average cost reduction is around 50% (normalised cost decreases from 51 to 26).

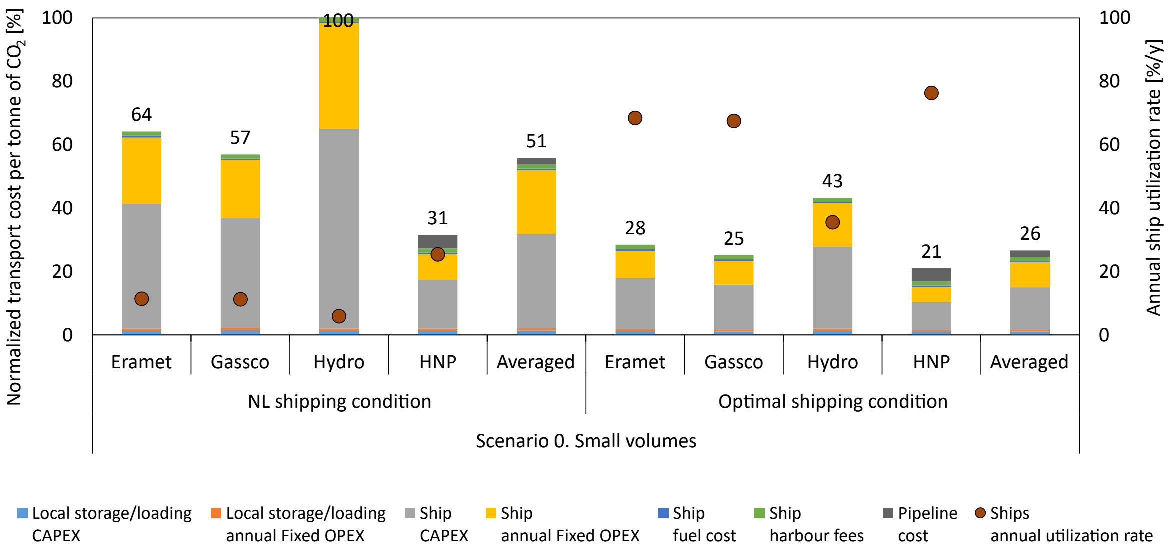

Figure 3-1: Normalized transport cost per tonne CO_2 for Scenario 0, small CO_2 volumes.

Figure 3-2 illustrates that the transport cost is further reduced when the amount of CO_2 transported is increased to the large volumes shown in Table 1-1. For the optimal shipping condition, the ship utilization rates are fairly similar to the small volume cases – the larger amount of CO_2 results in lower transport costs mainly due to economies of scale. It can also be seen that the cost difference between the Northern Lights and the optimal shipping conditions is reduced when the CO_2 volumes are increased. The cost difference between the two shipping conditions varies for the individual industries, but in sum, the average cost reduction is 25% (reduction from 24 to 18).

Overall, it is evident form Scenario 0 that, for both CO_2 volumes, ship and buffer tank sizes need to be customized for each site instead of being fixed to the NL shipping condition. Thus, for other scenarios, only the optimal shipping condition is presented and discussed.

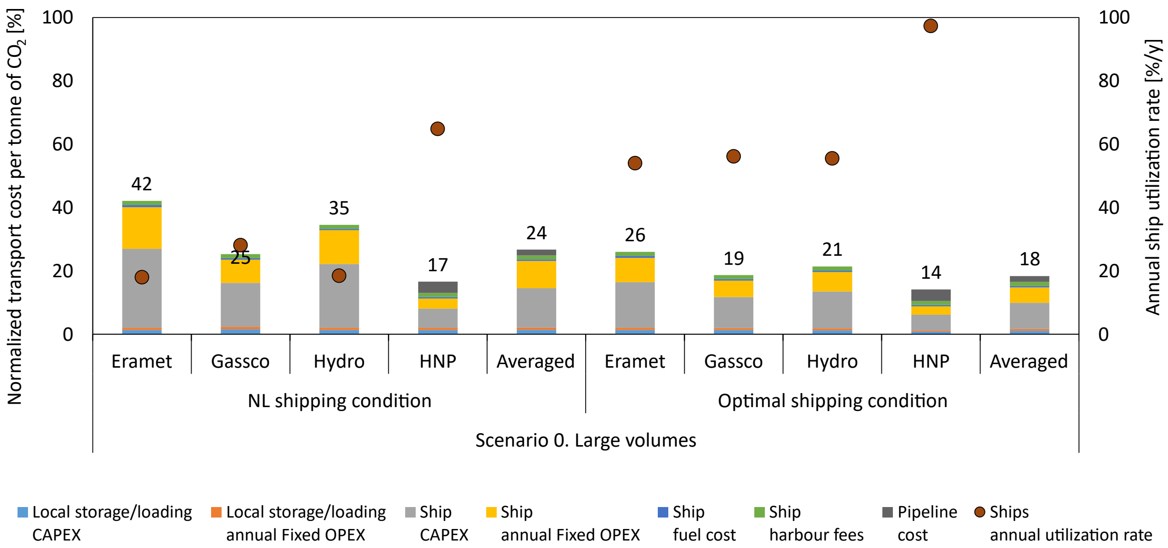

Figure 3-2: Normalized transport cost per tonne CO_2 for Scenario 0, Large CO_2 volumes.

3.1.2 Scenarios 1, 2 and 3: shared infrastructure

The results with shared infrastructure (Scenarios 1, 2 and 3) are shown in Figure 3-3 for the small volumes and in Figure 3-4 for the large volumes, alongside the Scenario 0 results for optimal shipping condition. For the small volumes in Figure 3-3, in Scenario 1, it is beneficial for all partners to include HNP in the shipping route, since the normalized average cost decreases from 22 to 18, compared to Scenario 1 without HNP. Also, Scenario 0 for HNP is more expensive (normalised cost is 21) than Scenario 1 with all partners. Mainly, the cost savings of the shared infrastructure are achieved by decreasing the total number of ships from four (Scenario 0) to one. It can also be seen that there is no significant difference in cost between the ship-based Scenario 1 and Scenario 2 with pipeline transport from Gassco and Hydro to HNP. The reason for this is that the small CO_2 volumes result in a relatively high pipeline cost per ton of CO_2 in Scenario 2, which counteracts the significantly decreased sailing time due to the reduced number of stops for the ship. As expected, Scenario 3 with a CO_2 terminal at HNP is the most cost-effective, since the distance to the CO_2 terminal is significantly reduced, which shows the importance of proximity to a CO_2 terminal.

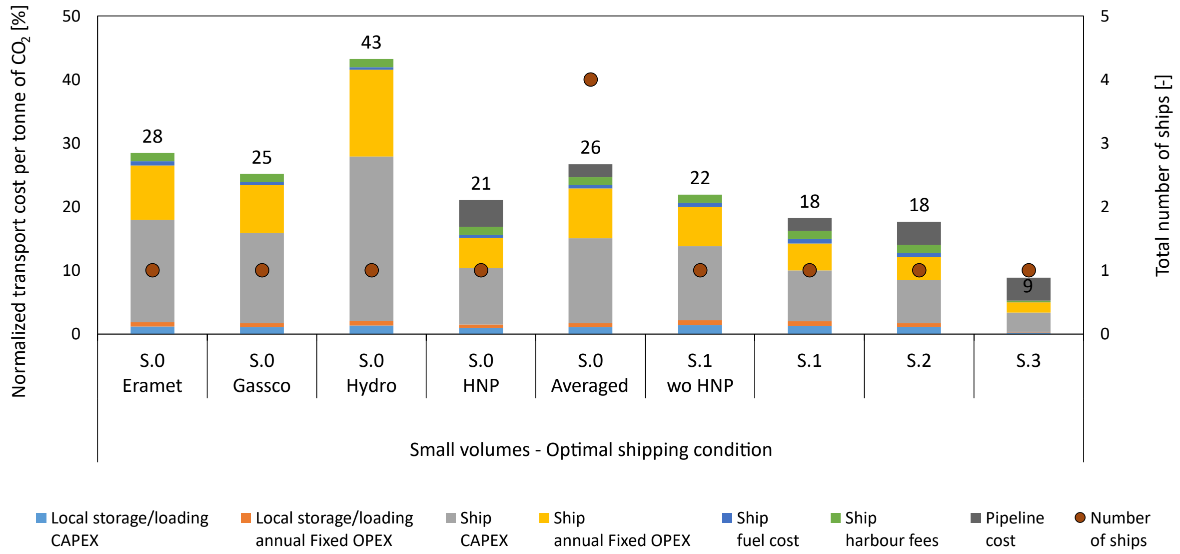

Figure 3-3: Normalized transport costs per tonne CO_2 for the small volumes at the optimal shipping condition, all scenarios.

When transitioning from small to large CO_2 volumes, there is indeed a cost reduction in almost all cases. The exception is when Scenario 1 includes HNP. In this case, the logistic cost per amount of transported CO_2 actually increases compared to the average cost for Scenario 0. This is mainly due to the long round-trip time with multiple stops, requiring large ships and buffer tanks. Scenario 1 also has only one ship less than Scenario 0 (three instead of four), which is an insufficient reduction to compensate for the cost increase of the extensive round-trip time. Instead, Scenario 1 without HNP is the most beneficial for all partners – the normalized average cost for Eramet, Gassco and Hydro is reduced to 14 while requiring only one ship, and the normalized cost for HNP with its own shipping between the HNP port and Northern Lights (S.0 HNP) is also 14.

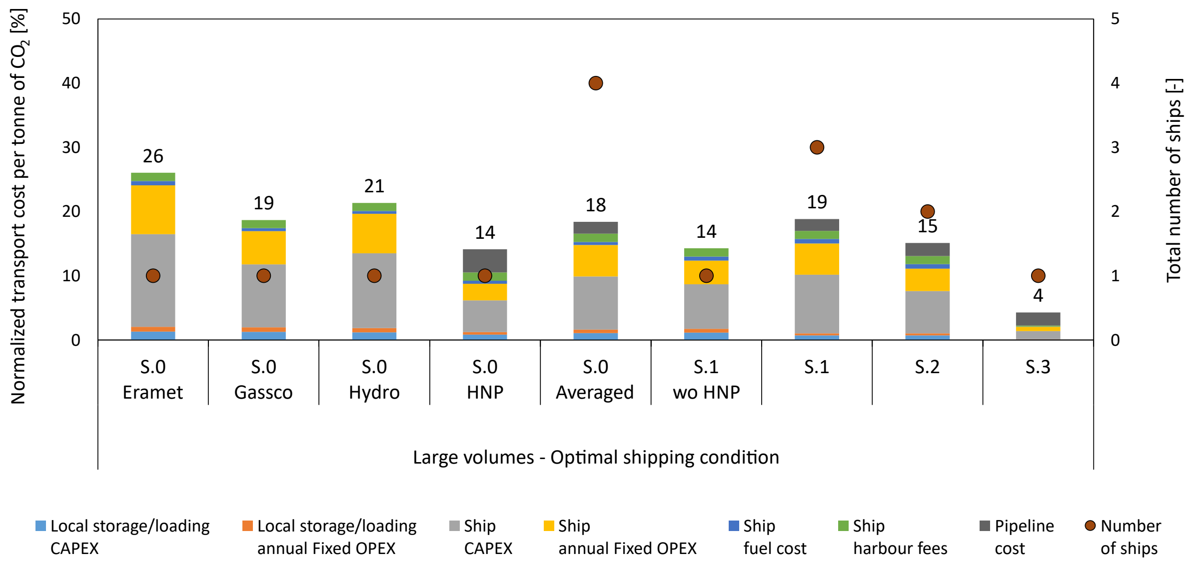

Figure 3-4: Normalized transport costs per tonne CO_2 for the large volumes at the optimal shipping condition, all scenarios.

The difference between Scenario 1 without HNP plus a stand-alone HNP (S.0 HNP) and Scenario 2 (pipeline from Gassco and Hydro to HNP) is relatively small for the large CO_2 volumes (normalized cost is 14 vs 15), and more detailed studies would be required to determine which is the most beneficial option. The best alternatives will also depend on the degree of coordination of timelines among the industrial partners for the implementation of CO_2 capture. It can also be seen in Figure 3-4, that as for small volumes in Figure 3-3, the lowest cost per ton of transported CO_2, as expected, is obtained when there is a CO_2 terminal at HNP.

This economic analysis of CO_2 logistics for the CCS Haugalandet project illustrates that the optimal transport scenario varies depending on several factors such as the volume of CO_2, transport distance, and route planning. However, it is found that shared infrastructure typically results in lower transport costs compared to the individual transport routes, except for the HNP large volume case.

3.2 Sensitivity analyses – sailing distances and CO_2 pressure on ship

Two sensitivity analyses are presented in this section: on varying transport distance and varying CO_2 transport pressure on the ship. The analyses are performed for the most low-cost logistic options - the large volume/optimal shipping condition cases for:

- Scenario 0 for HNP as a stand-alone case
- Scenario 1 without HNP (complementarity with Scenario 0 for HNP, ref to Figure 3-4)
- Scenario 2

3.2.1 Increased sailing distances to CO_2 terminal

As illustrated through the comparison of Scenario 3 with the other scenarios, the distance to the destination (CO_2 terminal for permanent storage) is a key factor in the transport cost. Therefore, the costs of the optimal scenarios selected for the large volumes are evaluated with different sailing distances under the optimal shipping condition. Figure 3-5 shows how the transport costs increase when the distance is longer than sailing to the Northern Lights terminal. Rotterdam and Iceland are indicated in the graph as examples, i.e., it is roughly 400 NM and 850 NM longer to sail to Rotterdam and Iceland, respectively, compared to Northern Lights. This wide range of transport distances represents alternative CO_2 terminals (also other than Rotterdam and Iceland) that may be available in the future.

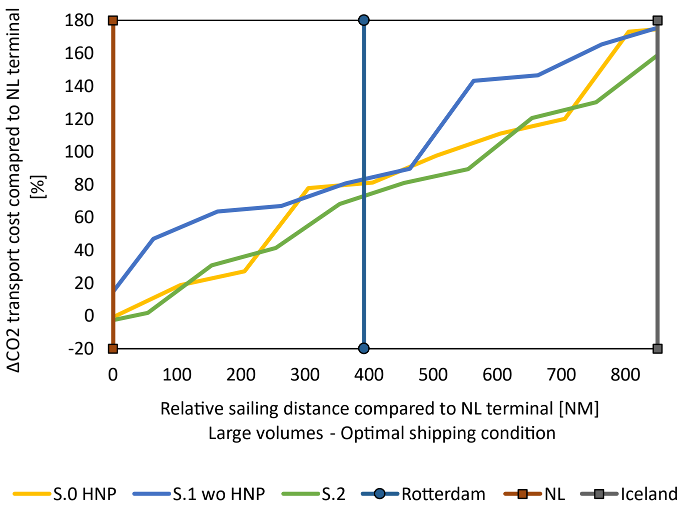

Figure 3-5: Transport cost difference per unit CO_2 for selected scenarios (large volumes) at the optimal shipping condition with sailing distances relative to the NL terminal.

The sensitivity analysis indicates that the transport costs rise rather linearly with the sailing distance. The linear increase in the cost curves with the same slope implies an increase in the optimal ship size while maintaining the number of ships to minimize the cost penalty with distance. Each change in the slope of the cost curves is related to an increase in the required number of ships due to the longer round-trip time with the extended sailing distance. Compared to the Northern Lights terminal, the transport cost is almost doubled when sailing to Iceland. This significant increase will require extremely low permanent storage costs for the terminal to overcome the cost gap compared to the NL terminal (see Figure 3-5).

Figure 3-5 shows that the most economical transport scenario varies depending on the sailing distance. For most distances to a CO_2 terminal located further away than Northern Lights, Scenario 2 provides the lowest transport cost compared to the other selected scenarios (stand-alone HNP (S.0 HNP) and Scenario 1 without HNP). Overall, this scenario may prove to be the most attractive. even in the longer perspective. This is the best scenario for a wide range of transport distances, which can reflect upcoming alternative terminals, and for large CO_2 volumes expected from potential expansion of capture facilities at sites. The pipelines from Hydro and Gassco to HNP in Scenario 2, are also in line with the development plan for a CO_2 terminal at HNP (Scenario 3).

3.2.2 Reduced CO_2 shipping pressure

Previous work on CO_2 logistics indicates the cost benefits of low-pressure CO_2 shipping[2, 12]. This cost reduction potential, however, is uncertain for the Haugalandet cluster due to the relatively short distance to the NL terminal. When the CO_2 shipping pressure is reduced from the industry standard (15 barg) to 7 barg for this work, the transport costs of the selected scenarios for the large volume case are seen to be decreased by up to 42%, mainly due to the reduction in the ship CAPEX and corresponding ship annual fixed OPEX (see Figure 3-6). This is a similar tendency with the low-pressure shipping found previously[2,11]. However, the HNP in Scenario 0 shows a marginal improvement with low-pressure shipping (about 20%) due to the large share of the pipeline cost on the HNP site. The cost improvement is more significant for Scenario 1 without HNP (40%) and for Scenario 2 (35%). In comparison, the normalized CO_2 logistics cost to the HNP terminal is 4 in Scenario 3 (Figure 3-4).

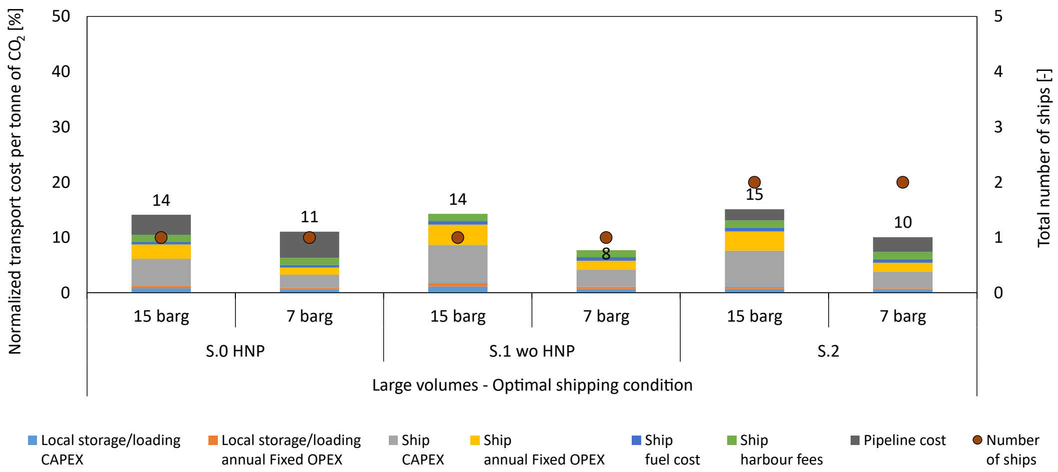

Figure 3-6: Normalized transport cost for selected scenarios (large volumes) at the optimal shipping condition with 15 barg and 7 barg CO_2 shipping pressure.

3.2.3 Reduced CO_2 shipping pressure and increased sailing distance

The advantage of low-pressure shipping becomes more significant as the sailing distance to a CO_2 terminal increases as presented in Figure 3-7. With 7 barg CO_2 shipping, the normalized transport cost can stay below 25 when sailing to Iceland (850 NM longer journey than the NL terminal), while the original case (15 barg) gives a maximum normalized cost of 40. In fact, the cost savings with low-pressure shipping becomes larger with increasing distance, reaching up to 15. Consequently, 7 barg CO_2 shipping (if/when feasible) is recommended for evaluation for any shipping distance to minimize the transport cost. In particular, Scenario 2 presents the lowest transport costs with low-pressure shipping at any sailing distance compared to the other scenarios in Figure 3-6, making this logistic plan the most economical for the reduced shipping pressure.

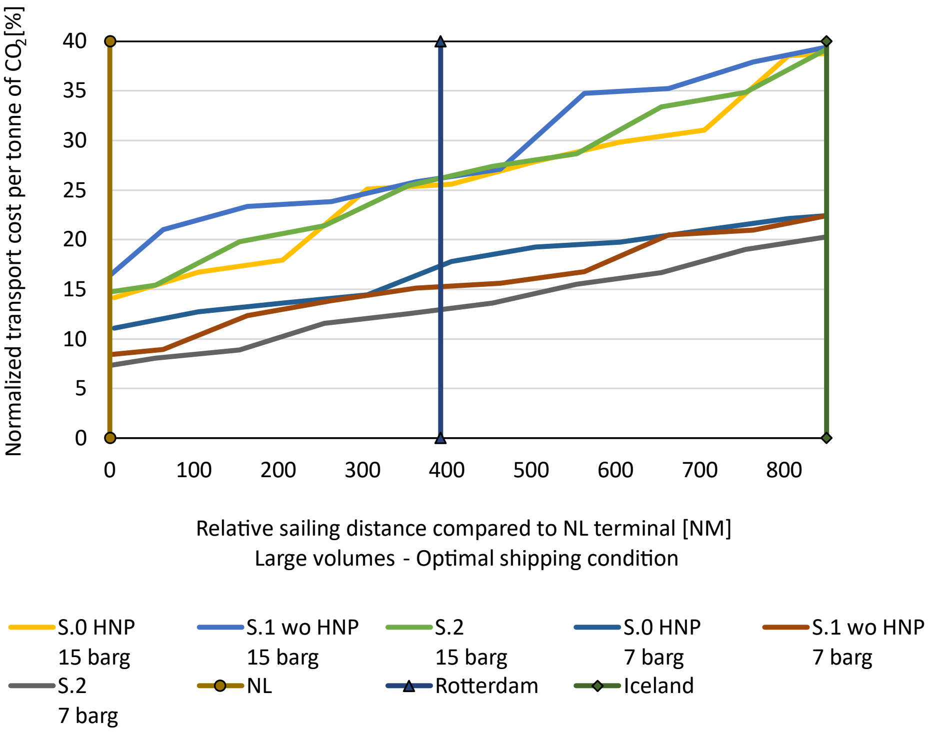

Figure 3-7: Transport cost between 15 barg and 7 barg CO_2 shipping pressure for selected scenarios (large volumes) at the optimal shipping condition with relative sailing distances compared to the NL terminal.

4 The wider scope of the Haugalandet CCS project

4.1 Local stakeholder meetings

CCS Haugalandet has throughout the project shared information to increase the public acceptance of CCS. This has been done through hosting several hybrid seminars open to the public, in addition to statements given at relevant conferences and in local media. The goal of these actions has been to enlighten the society about CCS and the status of work in the CCS Haugalandet project. There was a special interest for the seminars, engaging between 50-110 participants physically and online for each. The audience was a mix of local politicians and residents, interest-organizations, state agencies, CCS transport and storage companies, and other businesses looking into the industry. Recordings from the seminars have been published on www.ccshaugalandet.no.

Figure 4-1. Seminar at Haugalandet Næringspark 27 April 2023. Photo: Haugaland Næringspark.

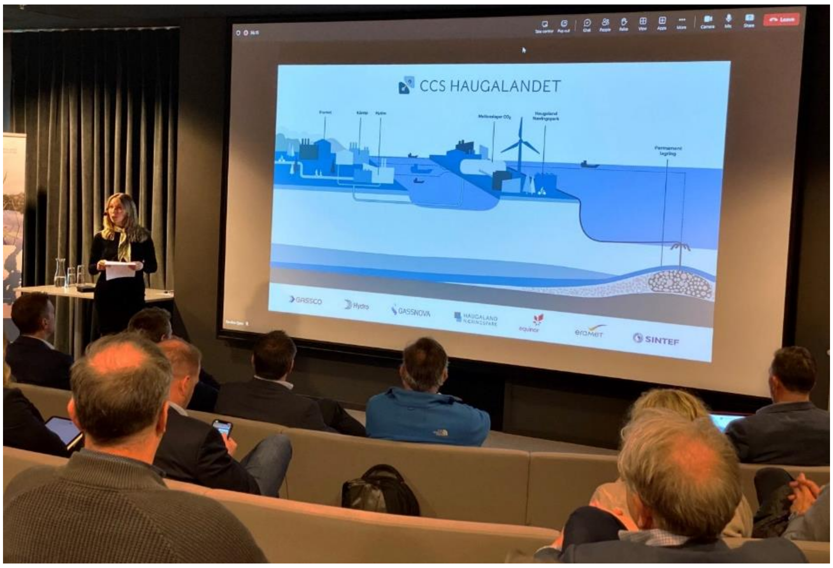

Figure 4-2. Project manager Karoline Sjøen Andersen presenting the CCS Haugalandet cluster. Photo Haugaland Næringspark.

4.2 Delivering CO_2 for storage on the NCS – what would it take?

Transport and storage of CO_2 constitute a considerable share of the levelized cost of CCS. Cluster cooperation for cost-efficient transport solutions, as presented in this report, is an important cost-cutting measure, but not sufficient for building a competitive business model for CCS.

During the project, CCS Haugalandet has been in direct contact with a range of companies for storage of CO_2 on the Norwegian Continental Shelf (NCS). The companies were invited one by one for presentations of their activities and discussions with the consortium. A learning from this activity is that there is sometimes an impression that the individual industrial CO_2 volumes from the actors in the Haugalandet region are too small to be prioritized by the transport and storage (T&S) operators. Thus, these small CO_2 volumes may not be compatible with the business models established by T&S operators, which tend to give priority to larger CO_2 volumes from continental Europe. This is most likely a general problem for most industries in Norway.

On the other hand, the Norwegian Environmental Agency (MDIR), has identified CCS as the emission reduction measure with the largest potential for achieving emission cuts in Norwegian industry and energy supply towards 2030-2035[1]. For this to be possible, Norwegian industry needs access to CO_2 storage at a reasonable cost. Governmental incentives could help securing access to storage facilities on the NCS.

Cost reducing measures along the full chain, from capture to storage, must be evaluated and realised. For this to be possible, in-depth knowledge building and sharing along the chain are required. A cooperation between Norwegian CCS clusters would be beneficial.

5 Conclusions

The CO_2 logistics scenarios explored in the CCS Haugalandet project highlight the key role of cooperation between the industrial sites for cost-effective transport of CO_2 to a terminal connected to a permanent CO_2 storage site. The optimal transport scenario varies depending on several factors such as the volume of CO_2 and sailing distance to a terminal. The study reveals that it is important to optimise the sizes of CO_2 transport ships and intermediate storage tanks at industrial sites based on sailing distances and CO_2 volumes. It also indicates that individual transport routes to the Northern Lights CO_2 terminal, without collaboration between industries, typically result in the highest CO_2 transport costs. The study also shows that the main cost driver for the transport cost is the ship CAPEX, which also affects the ship fixed OPEX.

The logistics scenarios were investigated for two sets of CO_2 volumes for each of the four industry sites in the CCS Haugalandet cluster, referred to as small and large volumes. In total for the four sites, the small volumes sum up to about 2 600 tonnes of captured CO_2 per day, whereas the large volumes sum up to 6 500 tonnes per day. The small volumes can be seen as a representation of an initial phase in the establishment of CCS in the cluster. For these volumes, it was found that one common ship, collecting CO_2 from intermediate CO_2 storage tanks at the ports of all four sites could be a favourable logistics solution, when delivering CO_2 to the Northern Lights CO_2 terminal. If CO_2 volumes increase to the large volumes, and a larger number of ships would be required to maintain the common sailing route, it was found to be beneficial for the cluster member with the largest CO_2 volumes (Haugaland Næringspark, HNP) to have its own ship for transport to the Northern Lights terminal, while the other three industries maintained one common shipping route.

For large CO_2 volumes, CO_2 pipelines from Gassco and Hydro to the HNP port is an option. This could reduce cost sensitivity if CO_2 ship transport to more remote storage terminals than the Northern Lights terminal is considered. However, the construction of CO_2 pipelines would require a separate study to ensure understanding of total scope, cost, and risk for this alternative. This includes the implications of CO_2 conditioning for ship vs. pipeline transport, and whether or not it would be beneficial with common CO_2 conditioning for ship transport from HNP.

It was also shown that there is a clear logistics cost benefit for the cluster if a CO_2 terminal is established at HNP. However, the total transport and storage cost would then have to include the transport cost from this terminal to the geological storage site and be compared with the use of other CO_2 terminals and storage sites. In the present study, this cost was not included.

It must be emphasized that the results provided in this report are scenario-based. The best logistics alternatives over time will depend on the degree of implementation alignment along the value chain.

CO_2 transport infrastructure, as the other parts of the CCS chain, needs to be amortized over long time periods (20-25 years). It is vital to collaborate in the cluster and together with industry networks and governmental entities, including public funding institutions, to create the conditions necessary for the infrastructure to develop.

The proposed way forward is to continue the cluster collaboration and the cooperation with authorities, other CCS hubs and local stakeholders. The study needs to be operationalised through the involvement of transport and storage operators, to refine the scenario constraints and cost estimates.