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THE NORWEGIAN FULL-SCALE CCS DEMONSTRATION PROJECT

Potential for reduced costs for carbon capture, transport and storage value chains (CCS)

Gassnova SF

Report No.: 2019-1092, Rev. 2
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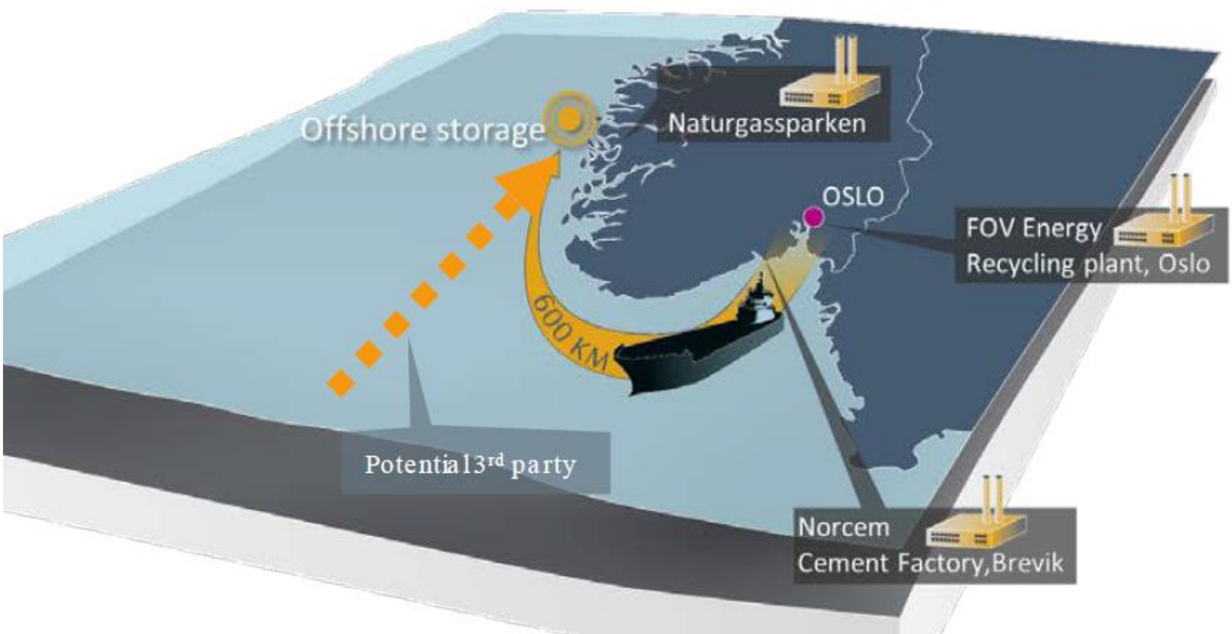

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Objective:

This report investigates the specific net present costs, Norwegian Krone per ton of carbon dioxide stored, for The Norwegian Full-Scale CCS Demonstration Project (NFSP). The goal is to estimate the potential short- and long-term cost reduction potentials for future CCS projects with the contribution from the NFSP-project. The estimates are based on investment and operational cost calculations from the industrial partners; the capture sites at Fortum Varme Oslo and Norcem Brevik, and the transport and storage project Northern Lights coordinated by Equinor with Shell and Total.

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EXECUTIVE SUMMARY

This report investigates the potential cost per ton reductions for stored carbon dioxide for The Norwegian Full-Scale CCS Demonstration Project (NFSP). The analysis indicates that a complete demonstration value chain will bring costs down through specific contributions to the technology and supply chain development of each part of the project. However, as the report discusses in detail the cost reductions will not be equally significant throughout the chain and the cost reductions are strongly linked to further capacity increase. Therefore, the analysis also estimates how the NFSP-project contributes to cost reductions with increased capture, transport and storage capacity from future CCS projects.

A demonstration value chain, with capture volumes from several capture sites, is necessary to benefit from scale effects, make the first steps for enabling cost reductions, and contribute to establishing a competitive CCS-industry. If only one capture site is realized, less learning will be brought forward to the industry, and the roll out of CCS will be slowed down. The demonstration project will contribute to cost reductions earlier and thereby accelerate the roll-out of CCS. In addition, the transport and storage infrastructure, with third party access and ship transport, will act as an enabler for capture from several potential emission sources in Europe.

This demonstration project is in many aspects a first-of-a-kind value chain with ship transport and capture from industry processes, which in this case is cement and waste-to-energy with partly biogenic emissions. Some of the technologies such as pipeline transport offshore and saline aquifer storage are technologically mature and have been demonstrated on a large scale previously but need to be commercialized further. The NFSP is expected to bring the costs of CCS further down through the industrial, commercial, regulatory and technical learning that has been going on for some years, and now increasingly with the Norwegian concept and feasibility studies, pilots and technology verifications.

The specific costs for the NFSP are relatively high compared with estimated costs for future developed full-scale capture sites and value chains. This is as expected. The project has been designed for maximum learning and technology development, and not optimized for the lowest specific cost for all parts of the value chain. The high specific cost per metric ton is due to the designed overcapacity for parts of the value chain, by the long distances from the capture site to the storage reservoir, small initial capture volumes, ship transport and an onshore terminal. However, utilizing the flexibility with ships for various demonstration capture volumes, other than the Norcem Brevik and Fortum Oslo Varme volumes, is important to reduce risk and enable various demonstration and pilot volumes.

The capture investments and operational costs contribute to more than half of the value chain cost. Capture is the least mature part of the value chain and is therefore the part of the value chain with the highest potential for future cost reductions. The capture cost represented in the following is the average of the two capture sites, which is a conservative approach since it has been identified potential capture projects with lower capture cost in the Northern Lights customer portfolio. However, the Norwegian capture costs are the most realistic current estimates for capture from cement production and waste-to-energy plants. The Norcem Brevik costs are lower than Fortum Oslo Varme mainly due to low cost waste heat available from the cement process.

The cost per ton is expected to decrease significantly when the value chain capacity is fully utilized from 0,8 to 5 million tons per annum (Mtpa). When estimating large scale capture volumes of 1 Mtpa the costs are expected to decrease further due to scale effects. The costs and cost reductions are estimated in stages to show the effect of various assumptions from increased utilization, optimization and wide industrial development. This will not be the case in the real world, where the various scale, optimization and learning effects will all gradually evolve together to provide cost reductions. The costs are both

estimated with an investor perspective and according to the Norwegian Environment Agency method (NEA).

Figure 1 shows possible cost reductions from the increased utilization and proposed optimization of the value chain, and a possible CCS industry development. The stages from 0 to 2 show the average cost per ton for the NFSP as the volumes increase from 0,8 to 5 Mtpa. Stages 3 and 4 show cost reductions as a result of second-generation optimized capture sites. This concept includes pipeline transport instead of transport by ships with both cost reductions and avoided costs. Such a transport concept with pipeline will typically be from a cluster with several point emissions, and a pipeline directly to the well and storage site. From this point on, industry learning curves are projected to show expected learning rates and cost reductions as the accumulated capacity increases (not accumulated volume). Based on this analysis the aggregated learning rate is expected to be at 10% for each doubling of capacity.

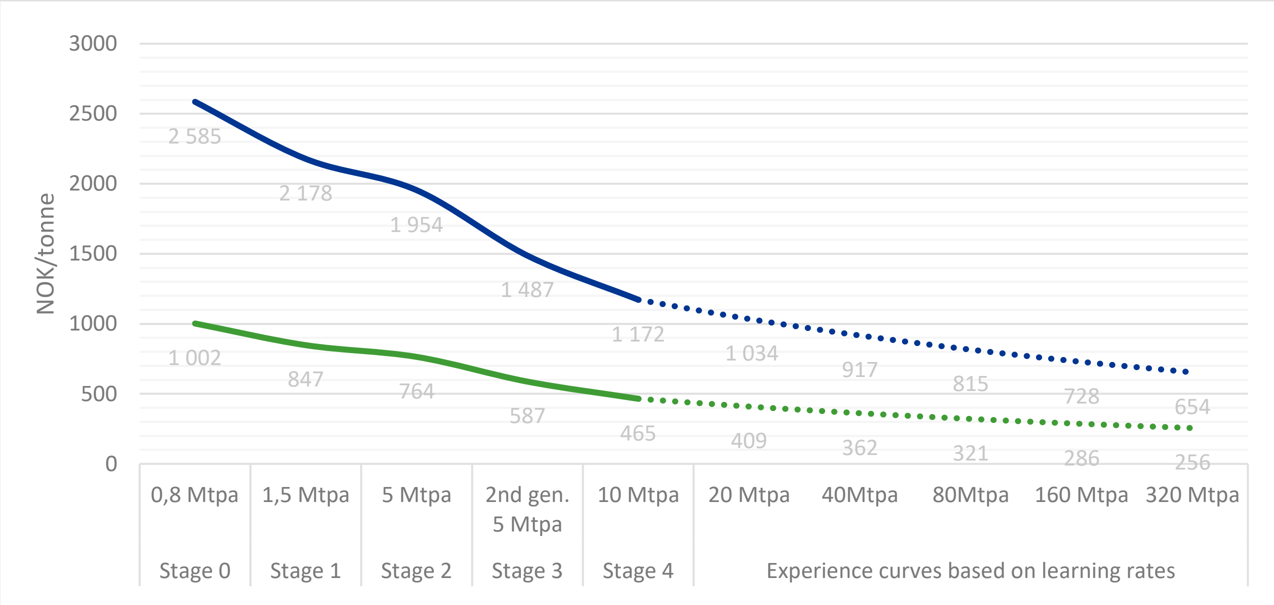

Figure 1 - Cost reductions estimates from capacity utilization increase, optimization and learning for increased CCS capacity. Investors perspective (high curve) and Norwegian Environment Agency method (low curve)

This demonstration value chain is expected to enable cost reductions for future and similar value chains. This is due to introducing improved or new technologies and the optimization of the value chain. The analyses estimate that future similar value chains will have cost levels half of the initial NFSP-costs. When there is a wide implementation of CCS internationally and the accumulated CCS capacity from 40-50 clusters results in 300 Mtpa for captured and stored CO_2, the analyses show cost levels below 700 and 300 NOK per ton, for the investor perspective and the NEA-method, respectively. To reach ambitious climate targets, it is expected that more than 1000 Mtpa must be captured from the European process and power industry in 2050.

The analysis shows that the Norwegian Full-Scale CCS Demonstration Project will contribute to cost reductions for future CCS projects and help accelerate the roll out of CCS. The NFSP will also contribute to improved understanding of identified risks with manageable measures to reduce these risks, scale effects after demonstration volumes are proven, the establishment of predictable regulatory regimes, evolving market and business models, and learning effects from technology development.

1 THE CARBON CAPTURE AND STORAGE VALUE CHAIN

1.1 Chapter summary

A key objective for The Norwegian Full-Scale CCS Demonstration Project (NFSP) is to foster technology development in an international perspective. The project has a design where technology, flexibility with ships reaching various demonstration capture volumes, and 3rd party access will be tested, instead of focusing on the lowest possible cost per ton.

There is already a CO_2-market today for carbonation of food and beverages, enhanced oil and gas recovery and other usage. The industry has also many years of experience with both of large-scale CO_2-pipeline and ship transport. However, the industry is now testing new and modified ways of capture, transport, storage with new compositions of CO_2 to reach cost parity with the cost of emitting CO_2. The demonstration projects will enable the development of a CCS industry, and without the NFSP being realized this timeline may be delayed.

1.2 Mandate, scope and timeline for the Norwegian Full-Scale CCS Demonstration Project (NFSP)

The Norwegian government wants to contribute to the development of cost-efficient technologies for capture, transport and permanently storage of CO_2. The government has an ambition to realize full-scale CCS demonstration in Norway, given that it will contribute to technical, market and regulatory experience internationally.

The ambition for realizing a demonstration CCS value chain has been made possible by pre-feasibility studies (2015), feasibility studies (2016) and concept studies (2017/2018). The NFSP partners are during October 2019 finishing the FEED-study. The decision gate 3.0 updated cost estimates are expected to be finalized and quality assessed during the spring of 2020. Evaluations and documentation from these phases will be the basis for an investment support decision for the project. The current schedule implies that the Norwegian Parliament is expected to decide for investment support during the fall of 2020. Figure 2 shows the historic timeline from pre-feasibility study to the proposed milestone for an investment decision and planned operation start-up. The cost reductions potentials and curves are based on the Decision Gate 2.0 cost data.

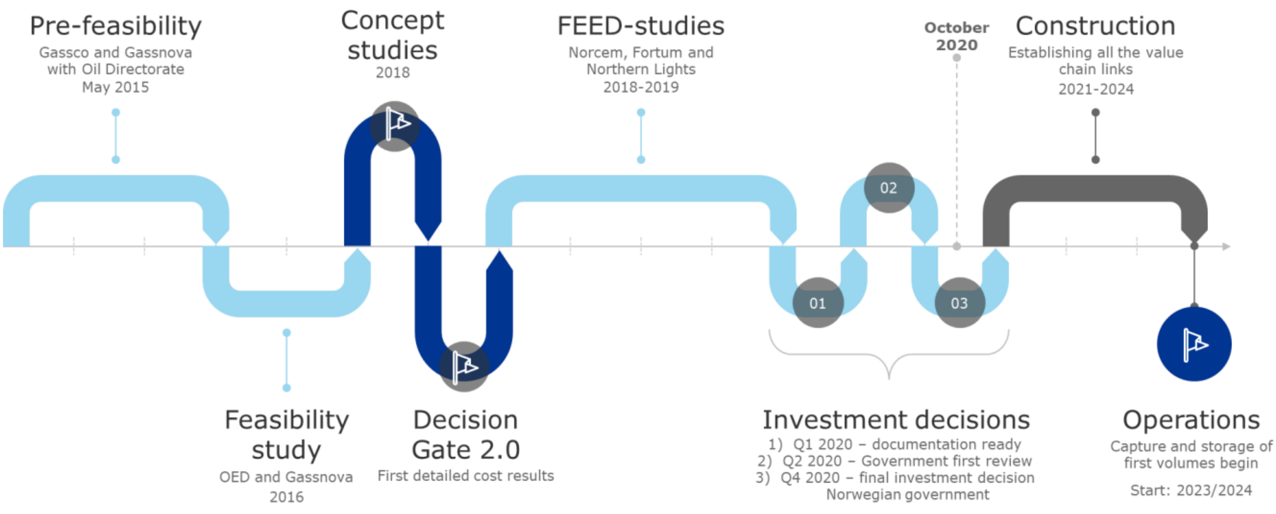

Figure 2 - The Norwegian full-scale CCS project timeline and process (Gassnova, 2019)

The societal objective for NFSP is to develop CCS as a cost-efficient measure to reach the long-term climate targets in Norway and EU, given the mandate and project overarching goals, which are:

1. Provide knowledge that shows it is safe and possible to implement full-scale CCS
2. Establish productivity gains for future projects from learning and scale-up effects
3. Enable learning from CCS regulations and incentives
4. Enable industrial and commercial development

As part of the work to reach these goals, the need to analyze costs and possible cost reductions has been identified. This is needed to get insight into future project costs, by showing possible cost reductions from this project. It is expected that NFSP will contribute by cost reductions both directly and indirectly for capture, transport and storage of CO_2.

The NFSP has been developed as a private public partnership where the Norwegian government together with industrial partners have explored and defined possible CCS value chains and solutions. The Norwegian government has defined overarching societal objectives together with the industry and found a common platform for the project. This has resulted in a unique project since it has:

1. Become a flexible and open-access transport and storage concept with excess capacity
2. Motivated industrial project owners with CO_2 capture volumes to be part of the value chain, which will increase trust and reduce costs for other CCS projects, and
3. Identified industrial proven technologies along the whole value chain, which increase the likelihood of a successful CCS demonstration.

The NFSP development has focused on reaching these goals and objectives, and not necessarily the lowest net present cost per ton. It may therefore have a higher net present cost compared to other value chain estimates. However, the value chain will provide important learning and cost reductions for future value chains.

1.3 The uniqueness of the Norwegian Full-Scale CCS Demonstration Project

The NFSP is unique in many ways. It is considered to have relatively high specific costs per ton CO_2, which is normal for first-of-a-kind demonstration projects. The NFSP development has focused on reaching the overarching goals and objectives, and not necessarily the lowest net present cost per ton.

The high specific cost per ton is first of all due to the planned overcapacity for parts of the value chain. In addition, the cost levels are affected by the long distances from the capture site to the storage reservoir, small initial capture volumes, ship transport and an onshore terminal. Utilizing the flexibility with ships for various demonstration capture volumes, other than the Norcem and Fortum Oslo Varme volumes, is important to reduce risk and enable various demonstration and pilot volumes. The costs will be even higher if only one capture site such as Fortum Oslo Varme or Norcem Brevik would provide capture volumes for the Northern Lights transport and storage infrastructure alone.

The project is based on captured CO_2 from Fortum Oslo Waste-to-Energy district heating plant (FOV) and the Norcem Brevik cement plant. These are both first-of-a-kind capture projects, which both plan to capture approximately 400,000 tons of CO_2 each annually.

The CO_2 will be transported by ships to an onshore facility at the Norwegian west coast, at Øygarden Municipality, as shown in the figure. Liquid CO_2 will then be transported by pipeline to the storage site and injected for storage in saline formations within the geological storage complex «Aurora» (Gassnova, 2019). The venture partners for the Northern Lights project with Equinor, Shell and Total are responsible for the planning and operation of ship transport, temporary storage at Kollsnes, pipeline transportation, CO_2 injection and storage, and monitoring to demonstrate safe and permanent storage (Equinor, 2019).

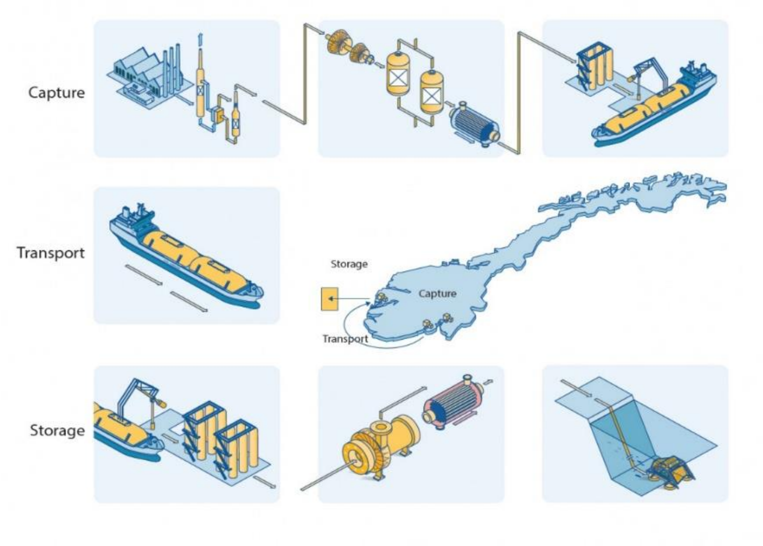

Figure 3 – The Norwegian CCS Full Scale Value chain (Gassnova, 2019)

The Northern Lights project is designed to have spare capacity for volumes beyond the design capacity for phase 1 and 2 (see below), which is to store at least 100 million tons of CO_2 over 25 years. The current project design (DG 2.0) is based on Phase 1, with flexibility to include additional volumes in Phase 2 subject to incremental investments for increased capacity.

Phase 1 consist of a concept to transport, inject and store up to 1,5 Mtpa of CO_2. Given a positive final investment decision from the Norwegian government and the project partners in 2020. Phase 1 is planned to be operational in 2023. Phase 2 would include capacity to receive, inject and store an additional 3,5 Mtpa of CO_2, adding up to a total of 5 Mtpa of CO_2.

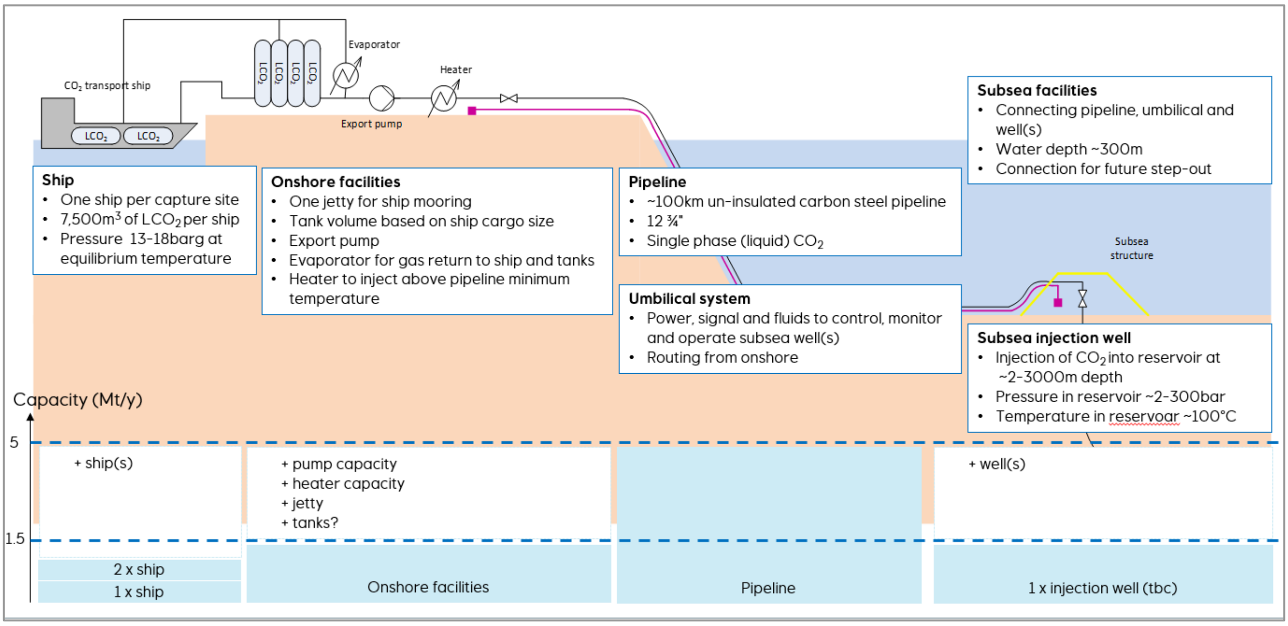

Figure 4 – The Northern Lights transport and storage concept (Equinor, 2018)

Three critical factors, for the total 5 Mtpa of CO_2 capacity, will be included already in phase 1. These factors are the basic functionality of the receiving terminal, offshore pipeline, and the umbilical to the offshore template. Both phases will offer flexibility to receive additional volumes from European CO_2 sources, beyond the phase 1 volumes (Equinor, 2019).

The transport flexibility offered by the ship solution allow for risk mitigation both in the development and operational phases. Given that availability of storage is a key enabler for individual CO_2 emitters to develop their capture facilities, this flexibility could accelerate the deployment of CCS across Europe. These transport connections would realize the first part of a cross-border CO_2 transport and storage network in the North Sea Basin (Equinor, 2019), (NSBTF).

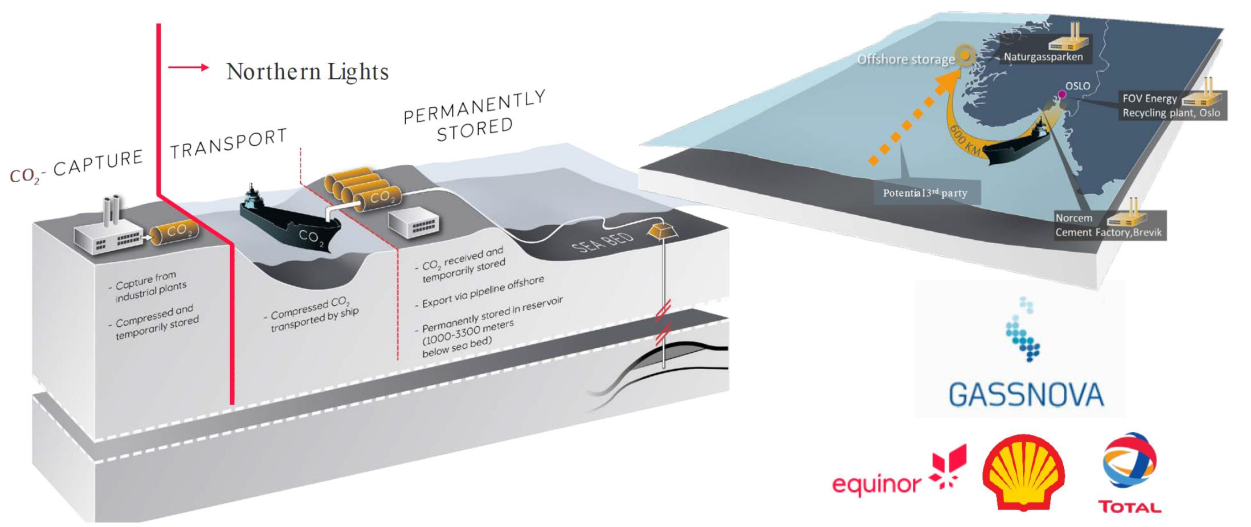

Figure 5 – Northern Lights Project Physical Value Chain Overview (Equinor, 2019)

1.4 The global CO_2 industry

The emerging CCS-industry may build on the global established CO_2-industry. Much of the otherwise vented high purity CO_2-streams from industrial processes is an opportunity for capture to kick-start the first CCS-demonstration projects. Volumes from the North European process industries and clusters may be part of the Norwegian Full-Scale CCS Demonstration Project, as additional volumes for increased capacity utilization for the Northern Lights project. The Northern Lights project have signed several MoU's with possible European process industry partners (Equinor, 2019).

Globally more than 220 Mtpa of CO_2 is used for various purposes which is a small percentage of all emissions (IEA, 2019). CO_2 is a by-product from commercial and mature industrial processes such as fertilizer and ammonia production, hydrogen production from natural gas, and ethylene glycol plants. This by-product is often reused in these processes if it is not sold for other uses or vented. Capturing CO_2 from power conversion emissions for food-grade purposes is not price-competitive with low cost sources (Economist, 2018). The largest consumer of CO_2 globally is the ammonia and fertilizer industry, which consumes 100 Mtpa for urea manufacturing, followed by the oil sector at nearly 80 Mtpa for EOR. Other commercial applications include food and beverage production, mineral carbonation and metal fabrication (IEA, 2019).

In the US most of the carbon dioxide used for CO_2 EOR is captured from CO_2 accumulations in the subsurface, while most of Europe's CO_2 for the food and beverage industry comes as a by-product of ammonia production and hydrogen. Those sources of supply tend to be seasonal. For most commodities, prices would then rise, encouraging more production, but there is no spot price that can adjust quickly since most of the gas is sold through long-term contracts (Economist, 2018). A hypothesis for cost reductions that can strengthen the synergies between CO_2 utilization and storage, may be to establish a spot market for CO_2. If a spot market for CO_2 would be established, for various purities and qualities, this could be an enabler of markets were storage providers and emitters may bid on volumes which could take the industry further in reaching cost-effective stored volumes.

The CCS industry may thus participate in establishing a larger market for CO_2 and provide services when these emitters need to reduce their emissions. There are synergies for technology and business model development and establishing a market, both ways, between the current CO_2-industry and an emerging CCS-industry. This sharing of technology and markets may increase and contribute to cost reductions for both the CO_2 industry and the carbon capture, transport and storage industry.

1.5 The development of CCS towards 2050

There are currently 19 operating CCS projects globally, four under construction, while additional 28 CCS projects are at various development stages in the Americas, Europe, Middle East and Asia-Pacific (Global CCS Institue, 2019). The Boundary Dam Carbon Capture and Storage Project and the Petra Nova Carbon Capture Project are two examples of CCS applied to power generation, while the remaining operating projects are on industrial production (ethanol, fertilizers, hydrogen, iron and steel, synthetic natural gas) and natural gas processing (DNV GL, 2019).

As the figure below shows, the Norwegian value chain may be an important step towards industrialization and large-scale roll-out of carbon capture, transport and storage. It will act as a value chain demonstration project contributing to learning and cost reductions. The value chain may enable the establishment of one of the first CCS clusters where the purpose is a permanent storage of CO_2 and not enhanced oil recovery (EOR). The third-party access to Northern Lights by ships can serve to facilitate early capture projects from several alternatives located in Northern Europe, close to the North Sea or Baltic Sea. The possibility of several following projects with low capture cost is not visualized in this analysis cost reduction curves.

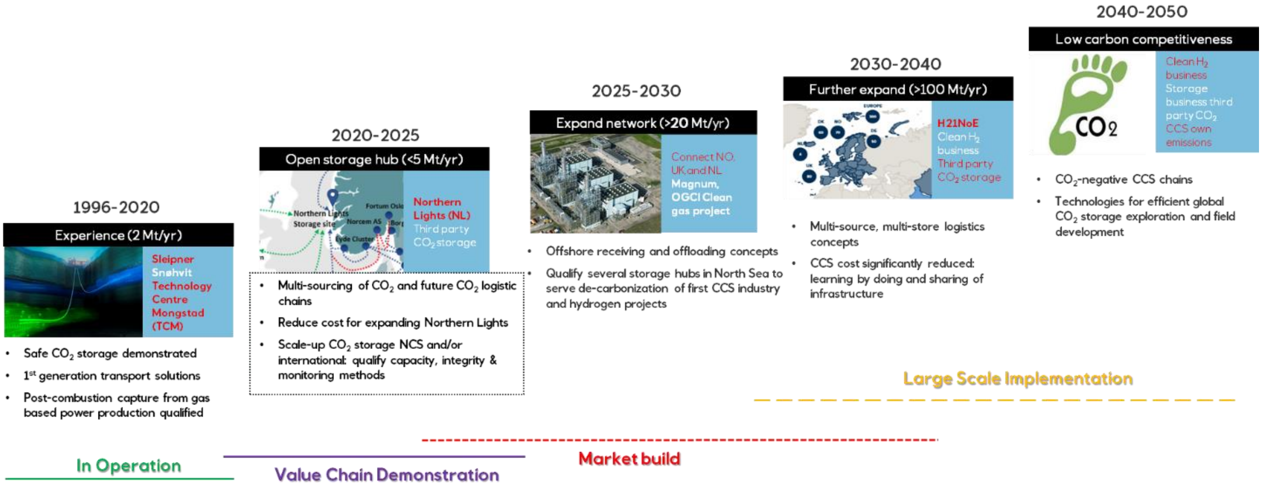

Figure 6 –Technology Roadmap towards a Northern Europe CCS industry (Equinor, 2018)

The future scale up and cost reductions depend first of all on an increased capacity utilization for the established Norwegian infrastructure. The next step would be to develop further clusters with the expansion of volumes with large scale capture and additional large-scale storage sites with direct pipeline injection. Large-scale CCS networks and an implementation with multiple clusters is needed to establish a commercial competitive CCS industry. It is also important to investigate the logistics in more detail, since it can be less expensive to use an easily accessible storage site close to CO_2 source, even if it has small capacity, than to transport CO_2 over long distances to a large established storage site.

Development of CCS technologies

The figure below shows a simplified and very broad and general status of more or less mature technology categories. It is important to know that there several Technology Readiness Level scales exist, e.g. ISO 16290 and various scales used by EU Horizon 2020, NASA, International Oil Companies and government research and innovation funding bodies. Here a general overview is shown, and that there is development needed for post-combustion, saline aquifers and pipelines offshore to reach bankable assets.

The purpose here is to illustrate that existing technologies, which may be mature and well developed for other uses, need to be developed further for CCS. As shown, the value chain parts, such as pipeline and ship transport, post-combustion with amines (which is the chosen technology for Fortum Oslo Varme and Norcem Brevik) with saline aquifer storage, has in general high technology readiness levels (TRL), but may move towards competitive commercial with the implementation of the NFSP. As one example, post combustion technologies has been employed commercially in gas sweetening since the 1970s and it is well known to the industry, but need to be further commercialized for CCS. Eventually the technologies and projects will reach competitive commercial levels with additional capture volumes and storage sites within some years of operational experience.

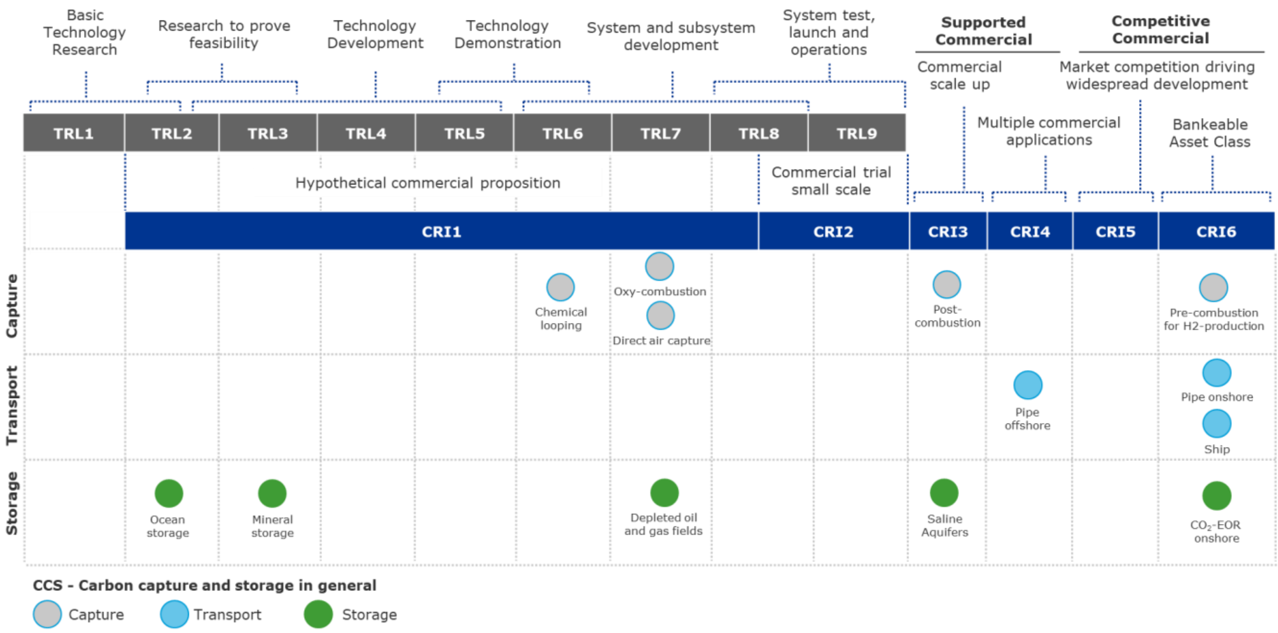

Figure 7 - Current development progress of carbon capture, transport and storage technologies in terms of technology readiness level and commercial readiness (DNV GL, 2019)[1]

[1] Figure based on (Royal Society of Chemistry, 2018) and (ARENA, 2014)

Figure 8 illustrates the first steps of what is needed to reach the first cost reductions and move towards commercialization enabled by the Norwegian Full-Scale CCS Demonstration Project. The demonstration effect from the NFSP is crucial to not postpone the cost reductions which is result of the combined technological, regulatory and commercial development. If the NFSP is not realized, it is highly likely that both key technological and regulatory learning will be delayed for several years.

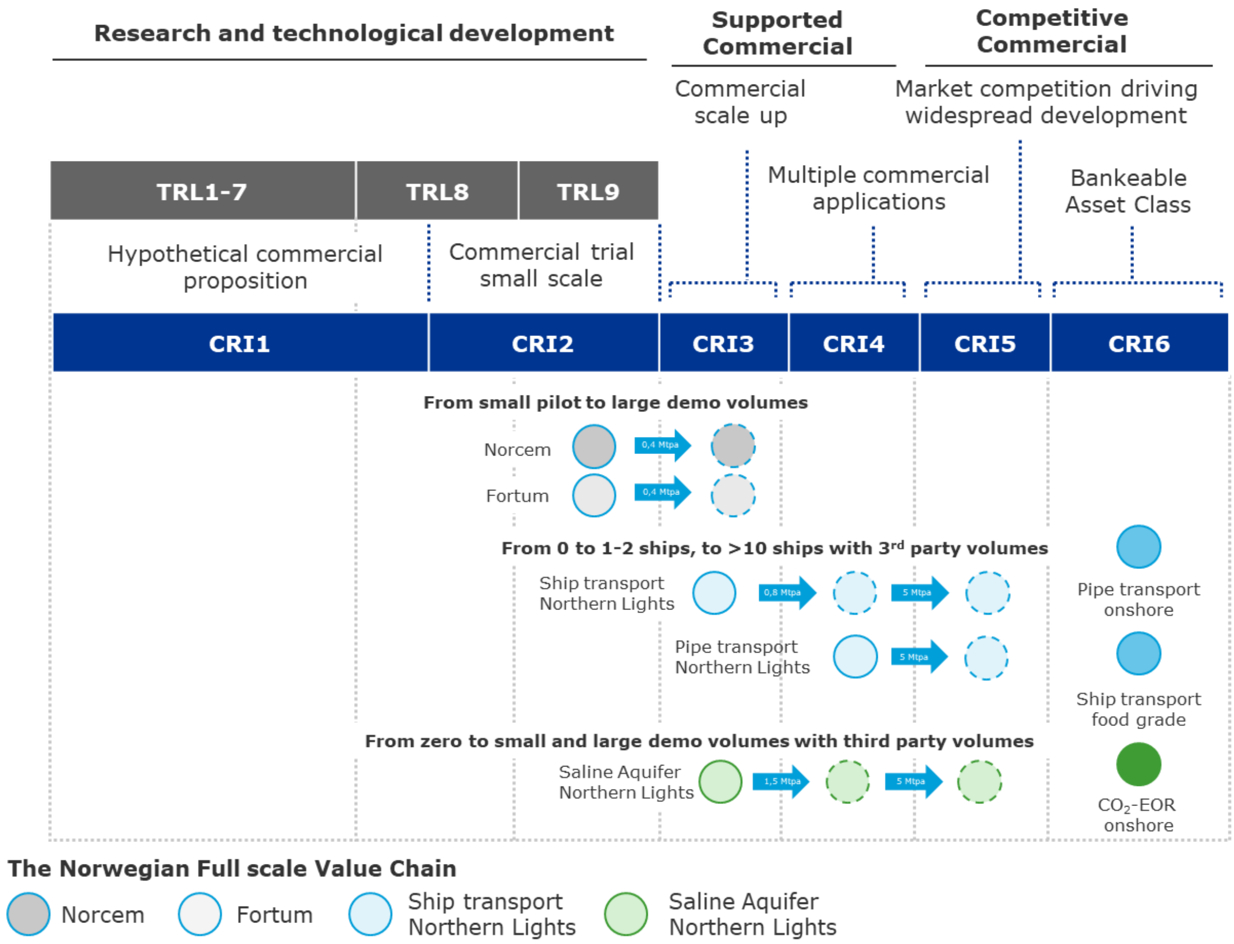

Figure 8 – The Norwegian Full-scale project may enable the CCS industry to develop towards a commercial competitive value chain (DNV GL team analysis)

For the NFSP to evolve from the mature technology readiness levels and partly defined commercial propositions to commercial scale-up within the next 5-10 years, the project must proceed as planned. The CCS industry needs continued full scale demonstration projects and regulatory support to reach high CRI-levels within the next 10-20 years.

The industrial partners must all make their own investment decisions. There are possible 5 or more investment decisions which must be made by the industrial partners, such as The Heidelberg Group, The Fortum Group, Equinor, Total and Shell. To reach the first level of supported commercial development, the Norwegian value chain must receive investment support, to transition through these steps, as shown in Figure 8:

- Capture: develop from small pilots to large demo volumes which will show capture costs and learning from first-of-a-kind cement and Waste-to-Energy plants

- Transport: increase from 0 to 1-2 ships, to >10 ships with third party volumes, where also the ships may increase in size from 7.500 m^3 to 30.000 to 40.000 m^3
- Storage: increase from NFSP volumes to an expansion with third party volumes. Each geological formation is unique, but the industry learns from demonstrating storage for each project. A novel aspect of the transport and storage chain is the temporary storage at Kollsnes.
- Value chain: first-of-a-kind complete process industry capture, ship transport and saline aquifer-based value chain

The transition from 5 Mtpa to the first 2-3 similar value chains of 5-15 Mtpa is crucial to establish a critical mass to support an industry moving towards the aim of 1000 Mtpa, if all European power and process industry emissions should be captured. When capture capacities and projects increase it would be possible to aim for competitive commercial conditions with market competition driving further widespread development.

Capturing most of the power and industry process emissions in Europe would require more than 1000 Mtpa to be captured. Some geographies already have carbon handling, transport and storage technology which are fully commercially developed with bankable asset class. However, this is food grade CO_2 transport, onshore CO_2 pipeline transport and the use of CO_2 for onshore enhanced oil recovery. It is essential with long term support for the next years to enable the CCS-industry to get a foothold and let the cost of carbon increase sufficiently to be an important driver for profitable CCS-business.

Development of capture

To reach further cost reductions, the development of capture must continue with a replication of projects and lessons learned, as well as larger capture volumes from large emitters after the initial demonstration has reached a certain maturity and have gained 5-10 years of experience. Low- and medium-cost CO_2 capture must early on go hand-in-hand with higher cost demonstration capture for increased capacity utilization for established storage sites. The first learnings contribute to larger scale capture sites. Eventually new industrial processes will be developed with pure CO_2 streams as byproducts which means no expensive post-combustion is needed, but the costs for carbon capture is part of the whole process cost.

The various capture technologies consist of groups of technologies, and a whole range of subsets of technologies. Post-combustion capture as a technology category for combustion processes is mature and is considered to have a high technology readiness level for CCS. This is based on the capture projects Petra-Nova and Boundary Dam. Even though the principles of the capture technologies are mature, there is still a lot to learn from applying these technologies at different emission sources, larger scale and optimizing energy use. At present, the biggest potential for cost reductions lies in applying the technology at many different industrial sources. Capture technologies need an industry to deliver to. This will foster both research on future large-scale solutions and optimization of existing technologies.

Future emerging large-scale technologies which may contribute significantly to lowered capture costs are oxy-combustion and the redesign of cement and steel-processes. Less mature capture technologies may also contribute to cost reductions long term.

Development of transport

CO_2 pipeline transport onshore for EOR and other uses and ship transport for commercial use is well developed. However, there is a need to scale up transport solutions for the Norwegian value chain step-by-step from 0,8 to 5 Mtpa, and further increases. When the demonstration value chain has been optimized from 5-10 years of operational experience and the cluster volumes increase the capture volumes, the development of CCS chains may increasingly focus on large scale multi-Mtpa projects with pipelines from source to sink. For large volumes and moderate distances, pipelines are the most cost-efficient transportation in most cases. There may be volumes from remote locations that would depend on ship transport to a nearby hub with further pipe transport.

Development of storage

Saline formations have been used for CO_2 storage at commercial scale projects, including Sleipner CO_2 Storage (offshore), Snøhvit CO_2 Storage (onshore capture, offshore storage) and Quest (onshore). The decision to inject for these and other CO_2 storage projects is not driven by oil and gas profits, but rather by cost savings from CO_2 taxes and quota prices, and other regulatory considerations. However, the new learnings will be to evaluate the business case for not including any oil and gas profits, and establish an open access storage infrastructure.

The injection and storage of around 1 Mtpa CO_2 at individual sites is technically viable, demonstrated by five currently operating industrial scale projects injecting into saline aquifer systems. The leading edge of research has thus moved beyond the viability of the technology which is now clearly demonstrated. The Quest project is reliant on government support and cannot be termed commercial at this time. The Sleipner and Snøhvit projects are commercial as a result of the offshore CO_2 tax regime in Norway. These projects are not commercially viable in a conventional sense and the technology is placed under CRI level 3, see Figure 7.

Carbon dioxide enhanced oil recovery, CO_2-EOR, has been practiced for many decades as a means to enhance the recovery of oil from depleted reservoirs, especially onshore. 14 of the 19 operating commercial-scale CCUS projects already use CO_2-enhanced oil recovery and there is a significant amount of existing experience and knowledge, which has enabled CO_2-EOR to reach the highest level of technology maturity and operates commercially with bankeable assets.

Mineral storage is at an early stage of development. Mineral carbonation can generate construction materials by conversion of suitable silicates. These routes are favored by thermodynamics and lead to stable products. Mineralization even offers opportunities to convert wastes, e.g., steel slags, with CO_2 to valuable construction materials. The challenges for mineral carbonization to be addressed are energy use, slow reaction rates and material handling. CO_2 storage in solid carbonates is expected to enhance public acceptance since this method of storage is highly verifiable and unquestionably permanent. There are currently no operational CCS projects with storage in depleted oil and gas fields, but storage of CO_2 in oil and gas fields has effectively been demonstrated through the global CO_2 EOR experience.

2 POTENTIALS FOR COST REDUCTIONS

2.1 Chapter summary

A full-scale demonstration project, such as the Norwegian Full-Scale CCS Demonstration Project, is necessary to reduce risk, gain experience and achieve cost reductions for CCS value chains. This demonstration project will provide necessary learning, experience and cost reductions to enable new value chains with higher volumes from larger capture plants and a considerable increase of transport and storage volumes. No industrial corporation will invest in large scale without demonstration, and it is normally more expensive to be the first and second mover than the following projects. The Norwegian rationale for supporting the project is to reduce risk, achieve learnings and pave the way for cost reductions for all parts of future CCS chains.

The relatively small initial demonstration volumes for the Norwegian value chain make the specific costs high (0,4-0,8 Mtpa), but a fully utilized value chain with 5 Mtpa will have considerably lower specific costs (NOK per ton per year). There are further potential cost reductions from the optimization of the value chain, and the wide deployment of CCS.

2.2 Methodology

One of the major barriers for CCS has been to establish a viable business model which can cover the costs for the handling of CO_2 through carbon capture, transport and permanent storage. The other major barrier is that there are high initial costs for demonstration projects and substantial first mover risks for the high investments which are needed for a complete value chain of permanent storage.

In this report, the cost per ton of CO_2 captured, stored and avoided for CCS is defined as the net present costs (NPC) of the investment (CAPEX) and operational costs (OPEX), divided over the amount of avoided emissions with both 4% and 8% discount rate. The two different calculation methods used are

- The «Investor's perspective», 8% discount rate for *both* costs and stored CO_2, 25 years horizon
- The Norwegian Environment Agency calculation method, 4% discount rate *only* for costs (stored CO_2 are not discounted), 25 years horizon (NEA, 2019)

This report uses the cost data provided by the industry partners to calculate the cost per ton CO_2 and then to further estimate possible cost reductions. The analysis combines three types of cost reductions as described in detail below. First the cost levels and the capacity utilization are estimated by the actual received industry data. Then an optimized full-scale value chain is estimated based on these cost data before learning rates are used for a possible future cost development based on a proposed roadmap for the CCS industry going forward (see chapter 1.5 above). The types of calculations and associated datasets are:

1) Norwegian value chain industry partner data (Stage 0-2)

a) The cost estimates from the capture projects Norcem Brevik (NB) and Fortum Oslo Varme (FOV), with transport and storage estimates from the Northern Lights (NL) project, is provided in a cost breakdown structure (CBS) for detailed analyses

b) The NFSP project represents a first-of-a-kind (FOAK) CCS value chain with ship transport, saline aquifer storage, and demonstration capture volumes from cement production and waste-to-energy (WtE)

c) Increased capacity utilization from 0,4 to 5,0 Mtpa implies a specific cost reduction with volume increases due to increased capacity utilization of the storage facilities. The capacity utilization consists of an increase from 0,8 Mtpa (both Fortum Oslo Varme and Norcem Brevik 0,4 Mtpa each), to 1,5 Mtpa (design basis for onshore terminals before pipeline transport to an offshore storage site), and 5 Mtpa (design basis for the offshore pipelines) for geological storage of up to 100 Mt

2) Optimization of the value chain (stages 3 and 4)

a) Cost reductions for a 2nd and 3rd value chain is estimated

b) The cost reductions are based on

i) The FEED-studies and identified value improvements projects (VIP) by the industrial partners in separate VIP-assessments.

ii) Scale effects and avoided costs if the projects were built directly to larger scale capture of 1 Mtpa (vs. 0,4 Mtpa as proposed today)

3) Projections based on industry input and a proposed CCS roadmap (stage 5 and onwards)

a) A CCS roadmap proposed by Northern Lights towards 500 and 1000 Mtpa, harmonized with the Energy Transition Outlook models for CCS globally

b) Towards an Nth-of-a-kind (NOAK) of the Norwegian value chain with an aggregated learning rate of 10% with experience curves for cumulative doubling of volumes

c) In addition, there will be a discussion of future of CCS technologies with new value chains, technology development, risk reductions and cost improvements by clusters and other effects such as technology shifts for certain parts of the value chain

The methodology process with its main steps is summed up in the figure below.

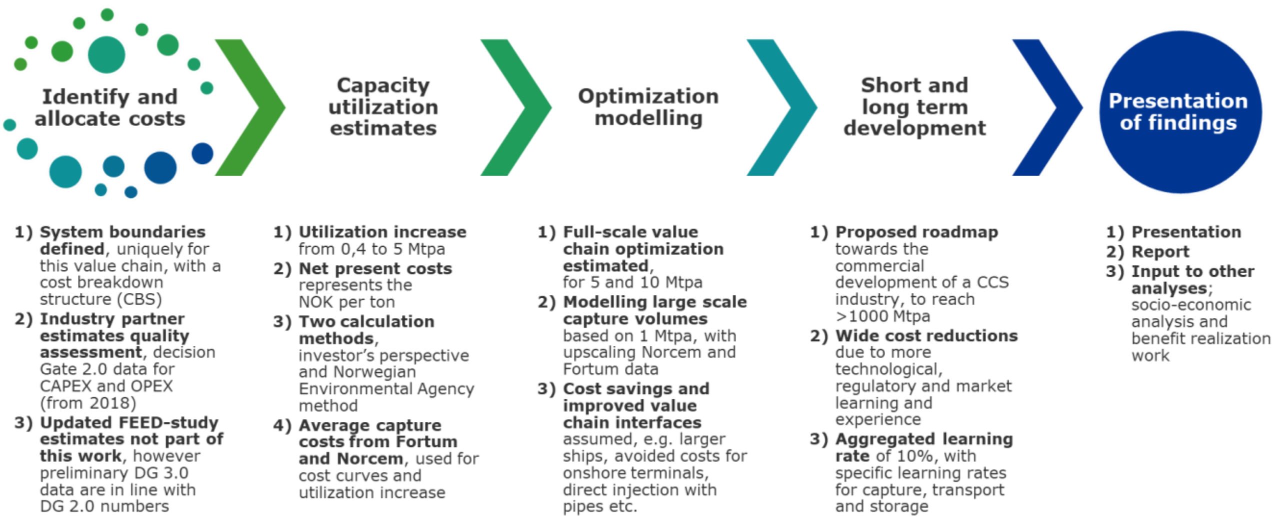

Figure 9 – The methodology and process for identifying cost reduction potentials

The cost estimates are based on a hybrid method where bottom-up data from the industry partners are combined with optimization modelling and learning rates and experience curves. Obvious and low hanging improvements are easier to discover while the technology is still relatively immature, and the first cost reductions are high. Historic development shows most technology development follows a learning rate when doubling the capacity or output which may illustrated with an experience curve (M. van der Spek, 2019). The longer the perspective the higher the uncertainty. Based on the assumptions and limitations of the method described above, cost levels and cost reductions are estimated and described below.

Experience and learning curves are a result of technology shifts and learning, which only happens with large scale rollout and industrialization of the various technologies. The estimates for technology shifts are not estimated in detail. The shifts may be, as shown by early pilot plants with integrated or high-efficient CO_2 capture, Leilac process for cement production, direct reduction processes with hydrogen for steel production and membranes or direct and efficient compression and liquefication for post-combustion processes. The commercialization of technologies may follow the same commercial development as has been done for sulfur and nitric cleaning, oil and gas refineries, as well as solar and wind power, consumer goods and electric vehicles, during the past 20-30 years.

In the model we have calculated the cost per ton in five stages before we have applied learning curves to the calculated cost for the last stages. It is worth noting that from stage 4 and onwards we are looking at value chains that lie some time into the future. A 10 Mtpa value chain with no ship transport is not realistic given current availability and geographical spread of potential capture sites. Stage 4 is only possible in the future but, reflects an optimization of a value chain based on the technology used in the Norwegian full-scale project. From this stage on we apply learning rates to the different part of the value chain, where the stages are shown below.

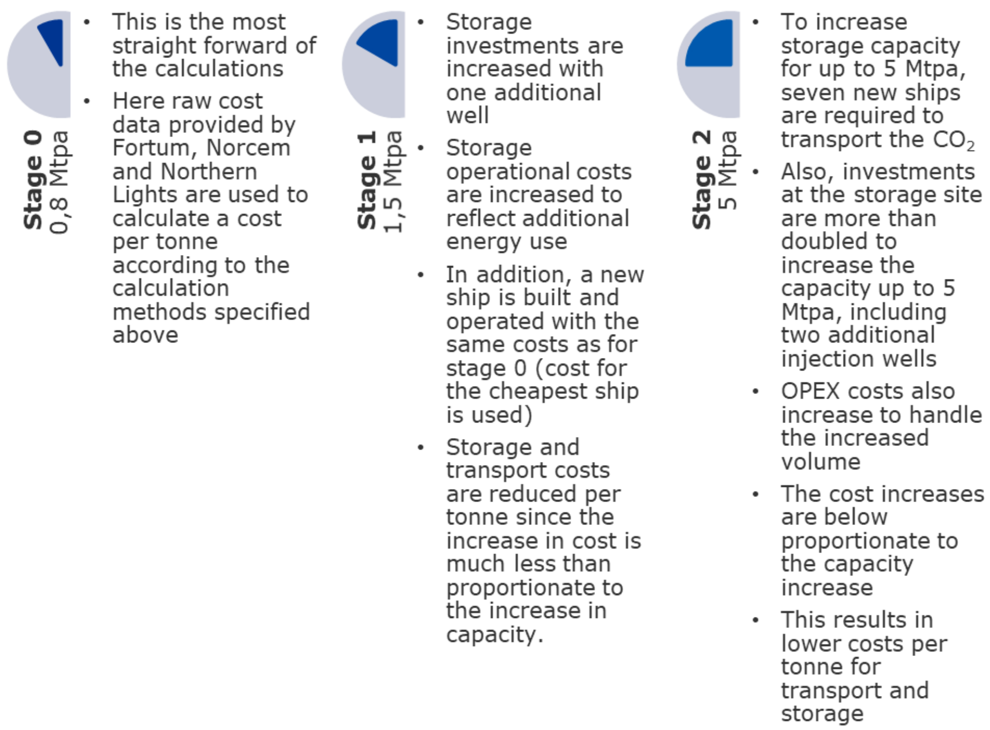

Figure 10 – Assumptions for the model stages, stage 0 to 2

Stage 3
5 Mtpa second generation

- Capture volumes are low compared with and optimally sized capture plant would look like.
- In this stage we have used the Cost Break-down Structures (CBS) from Norcem and Fortum to construct full scale capture sites by looking at how investments would increase for a full-scale site of 1 Mtpa.
- The model results show that
  - Investments increase by approximately 75%
  - OPEX increase by approximately 90%.
  - This is less than proportionate to the capacity increase of 150%, resulting in significantly lower costs per tonne.

Stage 4
10 Mtpa

- For stage 4 we have looked at what investments are needed in order for the storage site to have a capacity of 10 Mtpa
- Ship transport has also been replaced by pipelines
- Since ship transport has been replaced with pipes, temporary storage, transport and port investments have been removed from the capture cost CBS

Further Stages
Learning rates applied

- For the further stages we have applied learning rates to each of the different technologies in the value chain based on realized learning rates in comparable industries
- Learning Rates:
  - capture 15 %
  - transport 2 %
  - storage 3 %
- Learning rates describe how much costs are reduced for each doubling of accumulated capacity

Figure 11 – Assumptions for the model stages, stage 3, 4 and further stages

The report analyzes the technologies chosen by the industry partners and highlighted by Gassnova, with a general view on other technologies and solutions. Other storage solutions than geological storage in saline aquifers are not considered, which means that costs for geological storage in depleted oil or gas fields or geological storage through CO_2 injection for enhanced oil recovery (EOR) is not evaluated, even though these mechanisms may contribute to reduced costs and economically profitable business cases. However, EOR is in many cases not considered a climate measure with net volumes for storage. In the US storage through EOR is eligible for credits and it is also not excluded for credits under the clean development mechanisms (CDM). The NFSP and Gassnova mandate explains in further detail the reason for technology choices and the value chain design.

2.3 The costs of stored CO_2 for the Norwegian Full-Scale CCS Demonstration Project

The investment costs for two capture sites, with ship and pipe transport via temporary storage, to a well with storage in a saline aquifer is estimated to be about 14 000 MNOK. The operational expenses are estimated to be roughly 600 MNOK per year. The net present costs for a 25-year horizon is 1 000 NOK/ton using the Norwegian Environment Agency method, and 2 600 NOK/ton with an investor's perspective, rounded to the nearest hundred.

The capture costs contribute to a high share of the value chain cost. For the Norwegian Full-Scale CCS Demonstration Project, the capture investments and operational costs are more than 50 % of the total costs, even with investments for overcapacity for some parts of the value chain. Demonstration of capture is therefore crucial to reduce the overall value chain costs. Figure 12 and Figure 13 below shows the detailed cost estimates for 0,8 Mtpa. At 0,8 Mtpa there will be overcapacity in parts of the value chain. Low-cost volumes may increase the utilization capacity up to 1,5 and 5 Mtpa. Utilizing 3rd party volumes are important as a driver for more affordable CCS for all partners while experience and learnings are made for high cost capture volumes during the first 5-10 years of operation.

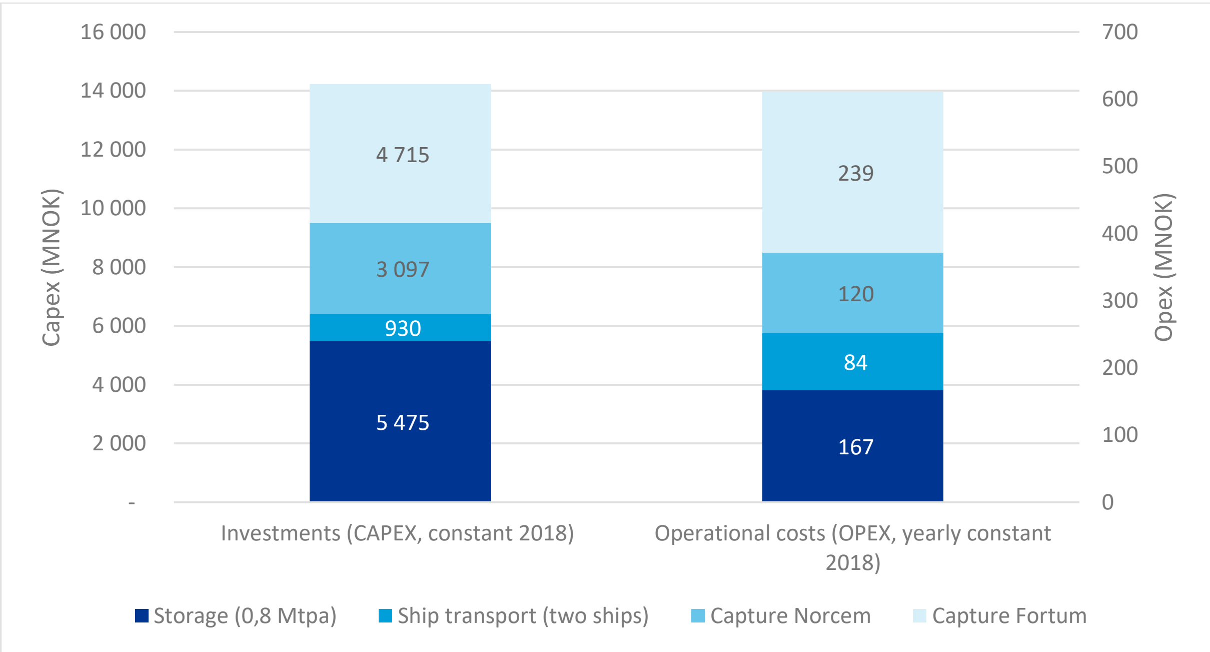

Figure 12 – Investment and operational costs for The Norwegian Full-Scale CCS Demonstration Project

Figure 13 shows the specific net present cost for an investor's perspective (left) and a cost calculation according to the method specified by the Norwegian Environmental Agency (NEA, 2019). The difference is that the investor's perspective uses 8% discount rate, and discounted avoided emissions, while the other perspective use 4% discount rate and do not discount avoided emissions. The Norcem Brevik costs are lower than Fortum Oslo Varme mainly due to low cost waste heat available from the cement process.

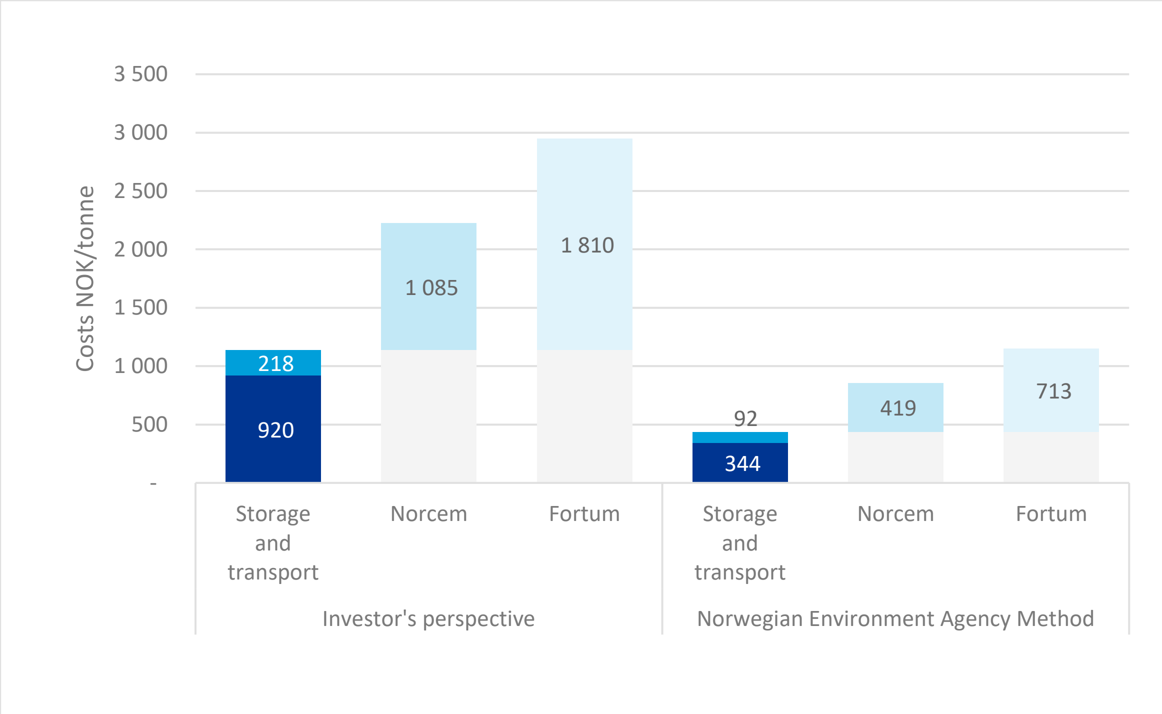

Figure 13 – Cost per tonne CO_2 for The Norwegian Full-Scale CCS Demonstration Project

2.4 CCS Cost reductions and cost drivers

The cost of CCS has been previously identified as a major barrier to its adoption. However, there are other potential barriers which are preventing its wider implementation as well. The CCS value chain consists of both established technologies and industry processes with well identified regulation, while other are novel with both unmatured technology and partly unregulated frameworks. This implies that some cost drivers and parts of the CCS value chain will have low learning and cost reductions for some factors, and higher for other. It is important to understand that the aggregated cost reductions for a full value chain has these variations embedded.

A CCS value chain may be designed with various configurations, with different high or lower cost parts of the value chain. A CCS chain involves the whole value chain from CO_2 capture and until final, permanent storage. As no CCS chains are identical, in addition to often being scenario and location sensitive, each chain must be evaluated individually for arriving on an optimal solution. Figure 14 shows the main categories of technologies for capture or source, transport and storage. These can be combined in a various of ways and give numerous possibilities for value chains and cost levels. The NFSP consists of some of the more costly elements of CCS value chains, as shown in the figure. These elements are also less mature than the lower cost technologies. This implies good possibilities for cost reductions and more reasonable cost levels for when new value chain is to be designed and built.

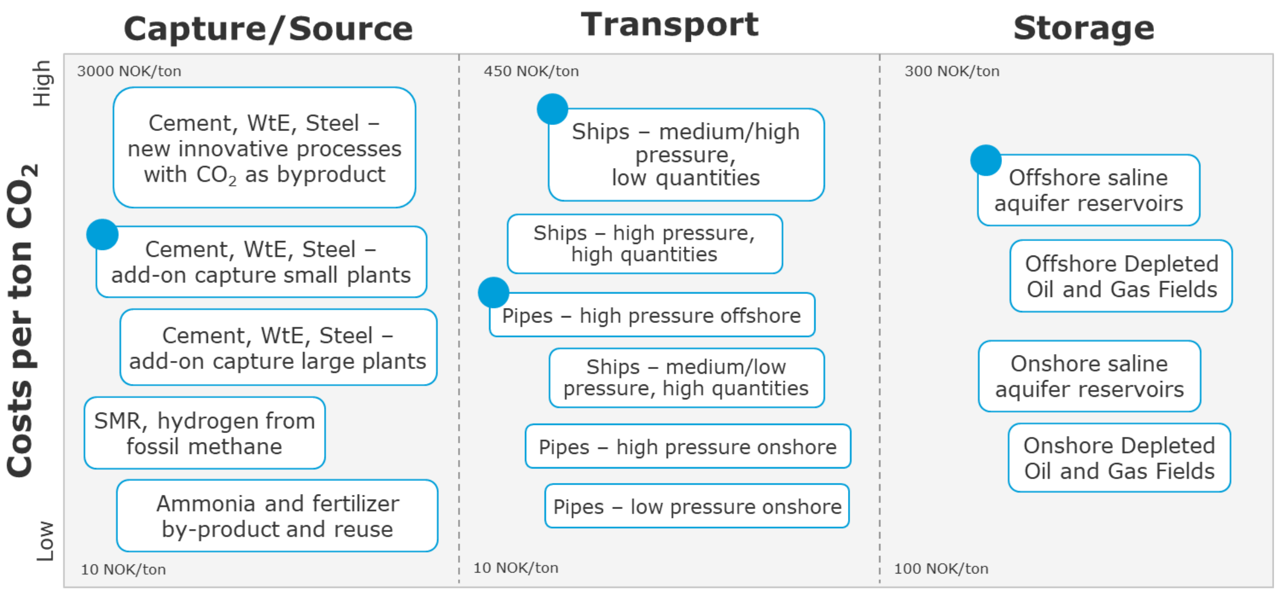

Figure 14 – CCS Value Chain Links Conceptual Cost Comparison, and the Norwegian project shown with blue dots (DNV GL, 2019)

2.4.1 Project specific cost drivers

Many elements of the Norwegian value chain are in the upper end of the cost scale for CCS. Figure 14 indicates these levels, labeled with blue dots, however as explained below, there are good reasons for this.

The analyses show that European 3rd party capture volumes are important for establishing a first-of-a-kind full-scale demonstration value chain. These volumes are available as currently mostly vented high purity CO_2-streams from for instance fossil methane-based hydrogen or ammonia production. The volumes may in many cases contribute to a lower average value chain cost for increased capacity utilization. It would not be cost efficient to increase the value chain capacity utilization with only high cost small demonstration volumes. The high cost capture volumes need more operational experience and learning with increased scale before more of these volumes would be provided cost efficiently for storage.

The general cost reductions for CCS may be lower investment or operational costs because of new or improved technologies or processes. The reuse of existing investments is also important. Improved technologies may contribute to lower heat or electricity consumption compared to an early pilot. New technologies or methods may also drastically reduce other operational costs. More specific for the Norwegian value chain, the cost reductions may be related to the topics shown in the figure below:

Capture (post-combustion as for the FOV and NB projects)	Transport with ships	Storage (with onshore terminal and pipes to storage site)
• Energy efficiency and free waste heat for the post combustion absorption process • Solvents loss and recycle ratio – low/high CAPEX vs. high/low OPEX • CO_2-concentration of exhaust gasses • Liquefaction and compression • Adaptation of industrial location for the capture plant • Temporary storage • Distance to ship terminal • Transport to ship transport (trucks vs. pipes)	• Ship design, with pressure specifications – low, medium and high • Quality and purity of CO_2 • Ship sizes and traveled distances • Ship lifetime and residual values	• Field location and knowledge level • Reservoir capacity and quality • Drilling of wells • Well plugging (new corrosion resistant materials) • Temporary storage • Pipe dimensions – size and pressure tolerances, corrosion resistance from CO_2 • Drilling of well • Monitoring and verification – high for initial projects

Figure 15 – Cost drivers for CCS value chains and the Norwegian value chain

The main reasons for the high specific demonstration net value costs are due to the following aspects:

Low specific costs (NOK per ton) has not been the main driver of this project. The goal has been to limit CAPEX of the demonstration project, and still get industrial and relevant learning, reduce cost for following projects and enable further industrial opportunities related to CCS. Government support for investments may have led to the optimization of investment costs rather than the net present cost (NPC). The effects may be lower investment costs, but somewhat higher operational costs than may have been the case with a stronger focus on NPC.

Small demonstration capture volumes

The capture demonstration volumes of 2x0,4 Mtpa are small and with larger capture volumes there are significant specific cost gains possible. This project is considered as a value chain demonstration project, which is much smaller in volume than large scale CCS projects with multiple capture plants, e.g. a value chain with 10 Mtpa volumes. The capture sites included in this project is based on a competitive process where industries could express their interest and compete to do concept and FEED studies with state financial support. The current industrial partners succeeded in this completion, together with Yara who withdraw after the concept phase.

A flexible and open-access transport and storage concept with excess capacity

Over-capacity for the initial 0,8 Mtpa volumes with 1,5 Mtpa for onshore terminal and 5 Mtpa for offshore pipelines and storage. This overcapacity has been decided in line with the projects objectives to yield cost reductions for following projects based on economies of scale. The added CAPEX was limited.

Logistics and transport

Different transportation solutions have been studied in the different project phases, including pipelines in the pre-feasibility stage. The selected transport solution with ships has been selected to make the CCS chain flexible, and because of relatively low volume of CO_2 over long distances and possible short timeframe. The design pressure and temperature envelope for the ships was chosen because this is standard conditions in existing CO_2 ships. One reason for high capture costs at the Fortum Oslo Varme site is due to the planned transport with trucks to the Oslo Harbor interim storage before the ship transport. Some of the costs with interim storage could be avoided for future projects with direct injection and pipe transport with larger capture volumes.

Storage in Saline Aquifers (SA)

The project has only screened potential storage sites with CO_2 storage in a saline aquifer. Depleted oil or gas fields might not have been considered because no potentially suitable sites with the desired total CO_2 storage capacity were available for CO_2 storage within the relevant timeframe. The potential for storage of CO_2 through CO_2 EOR was not considered, perhaps partly because it is not broadly considered to be a climate change mitigation solution. DNV GL considers that storage in saline aquifers and depleted oil and gas fields would broadly enable the same type and level of learning that could lead to future cost reductions.

Time between decisions and decision gates

Time between FEED-study and investment decision for government support (1-2 years) will drive the costs up since the organizations have to be on standby and have to keep high skilled workforce in place. In addition, there has been financial support for the study costs. Additional time has been spent for first time verifications by industrial partners and Gassnova, which would be needed to a lesser extent for a second project.

First of a kind

First generation technologies, especially small demonstration units are more costly than full-scale regarding specific costs. The demonstration capture volumes from Norcem and FOV, 0,4 Mtpa each, which may be realized, are still small compared to full-scale capture of typical 1-2,5 Mtpa or even higher volume point sources. There are additional risks for a first-of-a-kind demonstration project. Contingencies and allowances are expected to be higher for the first-of-a-kind and the following initial projects than for future projects which have better identified risks and measures to handle the risks. The competency and knowledge build-up within the industry partners' organization, Gassnova, Climit, research partners, and the relevant public agencies and ministries also takes time and is a costly activity but is an investment for further CCS-development. Regional high cost levels may also play a part where North Western Europe has higher cost levels than the global average.

Value chain segment boundaries

The storage costs include pipeline transport from the intermediate storage as well as the costs for the intermediary storage itself. Normally the system boundary is drawn closer to the well head. The capture sites also have transport from the capture site to an intermediate storage hub, especially FOV has costs included in the capture costs which normally is included in the transport costs.

Summing up, the full-scale project in Norway has not been developed for low costs per ton CO_2 stored, but has been developed to give relevant learnings, have excess capacity for third parties, and facilitate further industrial opportunities. The project is also based on the specific opportunities Norway has, to realize the project's goals, e.g. not have very large industrial emitters in a European scale. The capture concept is based on small scale add-on post-combustion capture. This is due to risk handling and the need to verify results before scaling up. Transport with ships has been chosen due to the flexibility and reduced CAPEX and commercial risks, and because ships allow easy and relatively low-cost upscaling of captured and stored CO_2 volumes. This upscaling should remain cost effective until the annual volumes of captured to be stored reach levels where building dedicated pipelines from capture hubs to a portfolio of storage sites become more cost-effective. For storage, only storage sites with CO_2 storage in saline aquifers have been explored.

2.4.2 Cost drivers related to regulation and market maturity

The cost of CCS can be reduced significantly with increased public sector allocation of certain CCS specific key risks. CCS will have a higher chance of success if new commercial models with modified risk reward structures including public sector support is implemented. The Norwegian government remove risk by investment support for the capture sites and the Northern Lights project. The investment support covers most of the investments for the whole value chain, as well as much of the FEED-studies. The investment support is paid out during the first 10 years of operations. Introducing commercial models which can transfer risk categories to the public sector may remove barriers that have prevented the private sector from investing in CCS. When the public sector takes responsibility for a larger part of the risks, project financeability would increase and the risk premium added to the cost of capital funding would be significantly reduced.

The CCS specific key risks that present the greatest challenges to overcome barriers to CCS development and drive down costs through reduced risk premiums, include:

1. Cross chain default (also referred to as ‘‘project on project’’) risk;
2. Cost sufficiency of financial securities related to the CO_2 storage permit and transfer of responsibility and liability;
3. Insurance market limitations for CO_2 transport and storage operations

The current strategy and approach by Gassnova and the Norwegian government is to handle these risks in a duly manner and contribute with risk sharing mechanisms. Risk (1) applies to all individual chain link elements, whereas risks (2) and (3) apply almost exclusively to the CO_2 storage aspects. Risks (1) and (2) would likely need to be absorbed by the public sector potentially for the lifetime of a specific CO_2 transport and storage, whereas risks (3) may be time limited and transferrable back to the private sector as practical experience is gained and operating confidence increases (Royal Society of Chemistry, 2018).

Success will depend upon the appropriate balance of risk between the private sector and the public sector considering the listed CCS specific key risks. It will also be important that models form a robust template for the long-term development of the CCS clusters. CO_2 transport and storage service providers also need a clear transfer of liability for the CO_2 until it is permanently stored.

Possible policy options include carbon trading, such as the EU Emissions Trading System (EU ETS) mechanism, or carbon taxation; targeted investment support, especially needed for the initial capital costs; feed-in schemes, which guarantee a fixed fee in order to compensate for the higher costs of the project when compared to conventional alternatives; a carbon floor price; low-carbon portfolio standard with tradable certificates; minimum standards, such as a CCS obligation for new installations after 2030.

2.5 Capture cost reduction potentials

The capture element of CCS accounts for most of the CCS chain cost. In power generation, for example, more than 90% of the overall cost of a large-scale CCS project can be driven by expenses related to the capture process. The current high capital and ongoing operational costs associated with the CO_2 capture plant in is a key target for improvement looking towards future CCS projects. Capture cost reduction can be essentially expected from two main efforts:

- Successful CCS demonstrations and additional industrial applications to gain valuable design, construction and operational experience ('learning by doing');
- Continuing R&D effort across a range of capture technologies;

The costs and cost reduction potentials in this report mainly focus on post-combustion capture with chemical absorption using amine-based solvents since this is the technology that will be used for Norcem and Fortum projects, and today it represents the state of art technology to capture CO_2 from flue gas. It is reasonable to assume that this technology will still represent the go-to technology for most of the next generation large scale projects until break-through concepts will be mature enough for large scale implementation.

Fully integrated chemical-absorption capture processes have been successfully demonstrated at large scales up to 1 Mtpa from at coal fired plant, most notably at Boundary Dam in Canada and Petra Nova in Texas. The actual range of application however is larger and includes major industries like cement, steel, hydrogen and ammonia - namely to all processes that release CO_2 in the atmosphere via gaseous emission stream.

2.5.1 Cost reduction from learning-by-doing and economy of scale

A critical mass of projects is essential to acquiring the cumulative project experience and lessons learned for subsequent success in deploying CCS technology. The first generation of large-scale CCS projects have gone through a 'learning by doing' process during design and construction. This experience can be expected to lead to significant cost reduction and performance improvement applicable to the next 'plant of its kind'.

Being a first-of-a-kind (FOAK) project, the experience and lessons learned from the design, construction and operation of the Boundary Dam project can be applied to further reduce the cost of a similar CCS project at the same site or at another location with similar characteristics. SaskPower, the project owner, has stated that a capital cost reduction of 30% would be achievable for a twin project (International CCS knowledge center, 2018).

It is unlikely that a project could be reproduced exactly in the same way since every project is site specific therefore some of the engineering solutions must be necessarily adapted depending and might not be exactly replicable. In this respect for a project replication, using the same technology but on a new facility, the cost reduction could be lower than the 30% stated by SaskPower.

Project replication would enable, amongst the others, the following cost-reduction opportunities:

- learning in project management and procedures
- replication of equipment design
- optimization of equipment and process design (e.g. less design margin or redundancy)
- optimization of process control and instrumentation (e.g. more flexible process)
- use of alternative construction materials (e.g. carbon steel instead of stainless steel)

Economies of scale benefits can be also achieved by scaling up the size of units. Once CCS is established, significant reductions in cost will be made by scaling up to plants. However, it should be noted that for several of the key equipment and systems required in a CCS plant, larger sizes are often not yet commercially available and, therefore, the currently available size "breakpoints" will limit scalability. With the widespread introduction of CCS projects, industry will have the incentive to push the limits on such equipment and develop larger and more cost-effective components like absorption columns or CO_2 compressors.

There are likely to be different optimal scales for different technologies but scale benefits on individual components could be of the order of 25% of capital costs for that particular component. Even where there are limits to the scale of the components, there will be potential additional benefits from ordering more than one component from a single manufacturer. Benefits in the order of a 15% reduction in cost for a second component (compared to the first) are regarded as reasonable (CCS Cost Reduction Task Force, 2013).

2.5.2 Learning rates for CO_2 capture plants

Reductions in the costs of technologies resulting from learning-by-doing and other factors have been systematically observed for industrial installations. Major factors contributing to cost reductions include, but are not limited to, improvements in technology design, materials, product standardization, system integration or optimization, economies of scale and reductions in input prices.

An IEAGHG study analyzed historical cost trends for several technologies which are in some ways analogous to technologies used in power plants with CO_2 capture (IEAGHG, 2006); the historical trends are shown in Table 1. CO_2 capture is often assumed to be technically analogous to post-combustion flue gas desulphurization systems for SO_2 capture, which had average historical learning rates of 12% for capital costs and 22% for O&M (operation and maintenance) costs.

Table 1 - **Summary of learning rates for capital and O&M costs for various technologies (IEAGHG, 2006)**

Technology	Learning Rate*		Cost Increase During Early Commercialisation
	Capital Cost	O&M cost	
Flue gas desulfurisation (FGD)	0.11	0.22	Yes
Selective catalytic reduction (SCR)	0.12	0.13	Yes
Gas turbine combined cycle	0.10	0.06	Yes
Pulverised coal boilers	0.05	0.07-0.30	n/a
LNG production	0.14	0.12	Yes
Oxygen production	0.10	0.05	n/a
Hydrogen production (SMR)	0.27	0.27	n/a

*Fractional reduction in cost for each doubling of total production or capacity.

The IEAGHG study concluded that the cost of CCS for power plant applications could be reduced by 13-20% for capital cost, and 13-40% for the overall cost of capture. The cost of capture is defined as the cost of a power plant without capture, minus the cost of a plant with capture at a point in time. The results are based on the assumption of additional 100 GW_e of power plant capacity equipped with CCS.

More generic learning rates analysis found in literature could be also used as reference for CO_2 capture technologies. The cost for each doubling of cumulative installed capacity of energy-related technologies has been showed to be reduced by up to 34% (with a median rate of 14%) (McDonald & Schrattenholzer, 2003). Learning rates of 20% as a general cost reduction factor has been documented for engineered processes (IEAGHG, 2004).

The generic learning rates seem to be consistent with pronouncements from the Sask Power company in Canada and the NRG company in Texas, which operate the first two large-scale CCS projects at coal-fired power plants. Both companies project a roughly 20 percent cost reduction for a subsequent CCS installation based on the experience to date at the Boundary Dam and Petra Nova power plants, respectively (Royal Society of Chemistry, 2018).

2.5.3 Improvement of current post-combustion technologies

As stated before, this report will mainly focus on the cost reduction potential of post-combustion capture using amine-based absorption process since this represents the current state of art technology to capture CO_2 from flue gas.

The capture process based on amine-based solvents works on a chemical absorption/desorption cycle. The sorbent is continuously routed between an absorber where it binds to the CO_2, and a desorber where the pure CO_2 is released by heating up the solvent. Such systems require a heat supply around 130-140 °C which is typically provided with steam. For each ton of CO_2 captured, about 2.5-4 MJ of heat are required. The energy requirement is not the only metric that defines the performance of an absorbent, but reducing this value is the primary goal of much chemical absorbent research.

Most components of amine-based capture process are proven technologies that have been used in a wide range of industries. The most used solvent in industrial CO_2 separation is 30 weight% aqueous Mono-Ethanol-Amine (MEA). However, in the last decade several technology developers have dedicated significant efforts to improve the "conventional" amine-based process. As much as a 25% improvement has been realized to date by many technology providers (CCS Cost Reduction Task Force, 2013).

Piperazine with amino methyl propanol (PZ-AMP) has been applied in several post-combustion applications and it is thus proposed as new benchmark solvent. The solvent PZ-AMP shows a CO_2 avoidance cost reduction of 22% for coal-fired, and 15% for gas-fired power plants, compared to a 30wt% MEA-based system. The energy requirement of the new benchmark is similar to that of current commercial blends (IEA GHG, 2019).

The improved processes are in fact already available on the market for scales of 0,1 Mtpa onwards, and provides enhanced performance regarding energy use, corrosion and degradation in comparison to the standard MEA process. The improvements are often reflected in reduced investment and operational costs. While cost for these processes could be improved further in the coming years through the "learning by doing", the margin for additional cost reductions due to optimization of the amine-based process performance is expected to be limited as technological limits are being approached.

2.5.4 Next generation capture technologies

CO_2 capture technologies are advancing. However, the next generation will for some time be based on traditional chemical absorption due to its maturity. New technologies will take some time to reach the development status of chemical absorption, and some technologies are developing with increased funding. With a demo-project for storage, these technologies may be accelerated with increased optimism for a CCS industry development.

For the next generation of CCS projects, cost savings are expected by continuing research and development efforts on promising break-through concepts. This includes processes that introduces more radical innovations regarding the working principle of the capture process and the materials employed.

This would include processes that are currently being developed from small pilot plant size to medium size demonstration plant.

In general, the innovation is pursuing significant cost reduction by more compact process, cheaper materials or lower energy requirements compared to state-of-the-art technologies such as solvents, membranes and solid sorbents.

While today most of CO_2 capture projects used post-combustion chemical absorption technologies on a wide range of applications, in the future we could expect to see a diversified portfolio of technologies that are tailored and optimized for a specific application. Table 2 provides an overview of various CO_2 capture technologies; technologies with TRL below 7 represent next generation technologies, some of them are achieving significant progress and are thus potentially expected to be ready for commercial use in the coming 10-20 years.

Table 2 – Overview of innovative CO_2 capture technologies (Global CCS Institute, 2014)

Technology	Test Stage	TRL
POST-COMBUSTION		
Amine-based solvents	Demo	7-9
Advanced amine-based solvents	Small Pilot	5-7
Amino-Acid salt solvent	Small Pilot	5-7
Aqueous Ammonia solvent	Large Pilot	5-7
Precipitating solvents	Lab/bench	2-5
Two-phase liquid solvents	Lab/bench	2-5
Catalysed enhanced absorption	Lab/bench	2-5
Ionic liquids	Lab/bench	2-5
Temperature or Pressure Swing Adsorption with solid sorbents (TSA/PSA)	Small Pilot	5-7
Supported Amine Sorbents (SAS)	Lab/bench	2-5
Calcium Looping (CaL)	Small Pilot	5-7
Membranes	Small Pilot	5-7
Cryogenic CO_2 separation	Lab/Bench	2-5
PRE-COMBUSTION		
Physical solvents	Demo	7-9
Ionic liquids	Lab/bench	2-5
Pressure Swing Absorption Based (PSAB)	Lab/bench	2-5
Ammonium Carbonate-Ammonium Bicarbonate process (AC-ABC)	Small Pilot	5-7
Temperature or Pressure Swing Adsorption with solid sorbents (TSA/PSA)	Lab/bench	2-5
Sorption Enhanced Water Gas Shift (SEWGS)	Lab/bench	2-5
Sorption Enhanced Steam-Methane reforming (SESMR)	Small Pilot	5-7
WGSRs membranes	Lab/bench	2-5
Membranes	Small Pilot	5-7
Cryogenic CO_2 separation	Concept	1-2
OXY-COMBUSTION		
Atmospheric oxy-combustion	Demo	7-9
Ion Transport Membranes (ITM)	Pilot	5-7
Oxygen Transport Membranes (OTM)	Lab/Bench	2-5
Pressurized oxy-combustion	Pilot	5-7
Chemical Looping Combustion (CLC)	Pilot	5-7

The reduction in cost of capture technology is particularly difficult to predict because technological development, by definition, is not a known quantity. Potentials up to 30% cost reduction are often claimed by technology developers. The United States Department of Energy has targeted a goal of reducing capture cost to around 35% with the new generation of technologies with further cost reductions arising from 'Transformational' technologies that are expected to be ready for demonstration in 2030-2035 (U.S. Department of Energy, 2013).

2.5.5 Main cost drivers in amine-based capture process

For the current projects using post-combustion amine-based capture processes, like Norcem and FOV, there are a number of major cost drivers that can significantly influence the cost of a project. Table 3 is an attempt to identify the main cost drivers, the impact on CAPEX, OPEX and the cost reduction opportunity.

Table 3 – Main cost drivers in amine-based capture process

Cost drivers	Impact on CAPEX/OPEX	Cost reduction opportunity
Flue gas integration	CAPEX	Reduce intervention on existing ducting, and minimize distance between gas tie in and capture plant Reuse existing stack for emitting the cleaned flue gas
Washing sections	CAPEX+OPEX	Reduce 1 section instead of 2 (Less stringent limit could allow this)
Energy optimization	OPEX	Recovery of waste heat from flue gas produced by the hosting facility Optimize energy integration by waste heat re-use and pinch point analysis
Cooling system	CAPEX+OPEX	Use water instead of air cooling when available
Materials	CAPEX	Switch to less expensive materials such as plastics and cement, in place of stainless steel
CO_2 purity	CAPEX+OPEX	Reduce CO_2 purification equipment if less stringent limits on CO_2 purity are possible
Plant integration with host plants	CAPEX	New build can benefit from optimization of plant integration in the early design phase
Solvent degradation	OPEX	Reduce solvent degradation (e.g. solvent cost)
Flexibility	CAPEX+OPEX	Design process with increased flexibility to adapt to load variations. This include partial capture coupled with plant load/production variations
Construction	CAPEX	Modular construction / off-site fabrication

2.5.6 NFSP capture cost reductions potentials

The Fortum Oslo Varme (FOV) is in the Front-End Engineering and Design (FEED) phase of evaluating a post-combustion CO_2 capture plant retrofit on an operating Waste-to-Energy (WtE) plant in Oslo, Norway. This WtE plant treats industrial waste and sorted residual waste from municipalities outside Oslo and provides heat for a district heating system serving approximately 200 000 inhabitants. The current design criteria comprise capturing up to 0,4 Mtpa of CO_2 which will require about 35-45 truck trips daily, depending on normal daily and seasonal load variations. The captured CO_2 will be liquefied on site and transported by lorry to the export quay in Oslo harbor, where it will be offloaded to temporary liquid storage and thereafter onto a CO_2 ship. The precise location of the CO_2 export quay is still being evaluated and will be subject to permitting and regulation. It will be designed for handling a CO_2 ship transfer every 3-4 days including a buffer storage capacity that satisfies goals of operating time of the CO_2 capture facility (Equinor, 2019).

Cost reductions from the Norwegian WtE capture project may be possible due to:

- Reduced costs without truck transport from capture site to harbor, with piping instead which may increase CAPEX but lower OPEX and lower net present costs (NPC) in total
- Optimized temporary storage, both at the FOV site and Oslo harbor
- Integration costs may be reduced (or increased) for future sites
    - Flue gas interconnection cost: due to limitations in space availability for CO_2 capture units near flue gas exhaust points, flue gas transport over long distances may be required in certain cases.
    - Steam supply integration for the CO_2 capture plant: steam extraction and connection for use in the CO_2 capture plant may result in significant modifications of the host plant (or the need for a secondary steam production plant) and can require transport over a significant distance, again, especially, in retrofit cases (Norcem and cement production normally benefits from waste heat)
- Flexible dispatch of power plants with CCS - CCS economics concerns flexible dispatch and part-load operation of power plants with CCS. Flexible dispatch and part load operation have large implications, both on the technical performance (lower efficiency) of the power and capture plant, as well as on their economics (higher costs of a produced unit).
    - FOV may benefit from waste heat as well, especially in the summer, when they have to burn waste, but cannot sell the heat, which could mean a more cost efficient capture or higher capture rates for spring, summer and fall emissions

The Norcem Brevik cement plant is the larger of the two cement plants in Norway. Yearly production volume is 1,3 MT of cement mainly delivered to the Norwegian market, but a part of the production is exported within Scandinavia and the northern part of Europe. Emissions of CO_2 is an unavoidable part of current cement production processes. Total emissions from the Brevik cement plant is approximately 0,8 Mtpa. Norcem plans for capturing 50 % of the emissions (0,4 Mtpa), based on the amine solvent technology developed by Aker Solutions. The capture process is energy extensive, and available excess heat from the cement production and the conditioning is enough to capture 50 % of the CO_2-emissions. There is a potential to increase the capture rate and -volume. Norcem Brevik has been involved in CCS since 2010 and have executed several studies. The FEED studies will be submitted fall 2019. The liquefaction unit is to be located inside the capture unit aside the cement plant. Buffer storage area is located close to the harbor operations, close to the loading area for the ship transport. (Equinor, 2019).

Future cement capture cost reductions

Cement production is a carbon intensive activity, with a carbon intensity in the range of 0,6–1,0 ton of CO_2 per ton of cement, with approximately 60% of this CO_2 associated with the calcination step. This means that even if the energy required to operate the process was entirely zero carbon, this would only reduce the CO_2 intensity by 40%.

One strategy to reduce cost for the cement industry is to use oxy-combustion conditions in calcination process to produce high CO_2 concentration stream, which would enhance CO_2 capture efficiency. New processes, such as LEILAC (Low Emissions Intensity Lime & Cement) for cement production, can generate high purity clean CO_2-output streams following this idea. The pilot project at Heidelberg Cement Lixhe in Belgium is one of the first to test this technology. Although this technology removes only about 60% of CO_2 emission, it is interesting as a cost-effective investment to cut a large portion of emission from cement plants. It will take time and development costs before the expected learnings and cost reductions are made, but this technology represents a shift for clean cement.

2.5.7 3rd party capture volumes

CO_2-capture represents a large share of the total CCS costs. The identification of low-cost volumes is important to enable CCS value chains, especially the first demonstration volumes which have comparable high specific costs before learning, scale-up and operational experience reduce the specific costs. The 3rd party capture volumes from the European industry may help commercialize the Norwegian value chain and CCS-value chains in general. Some process industry capture volumes are represented by industry processes where CO_2 often is vented from the process and available in high concentrations. Some industry processes where this is relevant is ammonia production, some steel production processes and hydrogen production from natural gas steam reforming.

The analysis shows that European low-cost capture volumes are crucial for establishing a first-of-a-kind cost-effective full-scale demonstration value chain. These volumes are available as currently mostly vented high purity CO_2-streams from for instance fossil methane-based hydrogen or ammonia production. The volumes may contribute to a lower average value chain cost per ton for increased capacity utilization. It would not be cost efficient to increase the value chain capacity utilization with only high cost small demonstration volumes. The high cost capture volumes need more operational experience and learning with increased scale before more of these volumes would decrease the costs. Since it is in the high cost and high-volume industries the potential for learning and economies of scale is highest, it is also within these industries that the value of a demonstration project is greatest.

The Northern Lights project has signed Memorandums of Understanding (MoU) with specific capture volumes, shown below with other possible volumes.

3,7 Mtpa — Low cost volumes

Port of Antwerp
Hydrogen from natural gas Demo volumes of 0,4 from Air Liquide and 1-2 Mtpa from Fluxys, Capture costs of €10-40 per ton CO_2 (ready for ship transport)

Ervia – Cork in Ireland
Hydrogen from natural gas to refinery, 0,3 Mtpa demo volumes Capture costs of €10-40 per ton CO_2 (ready for ship transport)

H2M Eemshaven
auto-thermal reforming of natural gas representing up to 2 Mtpa of CO_2 from 2025 onwards

Additional (no MoU)
Ammonia production (e.g. Yara), other specific point-emissions at refineries and industry clusters

4,5 Mtpa — Medium to high cost volumes

Preem Lysekil and Gothenburg Refinery
0,5+0,1 Mtpa pilots
Unknown cost levels

Stockholm Exergi
Wood waste, as FOV
Small test volumes Q3 2019, then 0,8 Mtpa
Possible cost levels of 1200 SEK per ton

ArcelorMittal Dunkerque
0,5 Mtpa

ArcelorMittal Gent
0,4 Mtpa

ArcelorMittal Hamburg
0,2 Mtpa – new steel process

Port of Antwerp and Fluxys
2 Mtpa

2,7 Mtpa — Norwegian Demonstration volumes

Fortum Oslo Varme
Cost levels of 1810_{INV} / 713_{NEA} NOK per ton captured at location ready for ship transport Oslo Harbor, 0,4 Mtpa

Norcem Brevik
(Heidelberg Cement)
Cost levels of 1080_{INV} / 419_{NEA} NOK per ton captured at location ready for ship transport Brevik Harbor, 0,4 Mtpa

Additional Norwegian mixed cost levels
from clusters (no MoU)

- **Borg CO_2**
  0,1 Mtpa
- **CO_2 Hub Nordland**
  1,2 Mtpa from 12 locations
- **Eyde Cluster**
  0,6 Mtpa

Figure 16 - CO_2 capture volumes which are, or may be, a part of Northern Lights

The Port of Antwerp is hosting Europe's largest integrated fuel and chemical cluster. The industrial cluster is highly integrated and is among others home to the production of transportation fuels (refining), base and fine chemicals, polymer and plastics, fertilizer and industrial gas production. The total industrial emissions in the Port of Antwerp amount to approximately 15 Mtpa of CO_2, of which more than 1 Mtpa are estimated to be high purity CO_2 sources. Initial volumes of CO_2 that can be captured in the Port of Antwerp are estimated at 3 Mtpa but can increase when carbon capture technologies would be further implemented. The CO_2 transportation capacity of the local CO_2 pipeline (backbone) may be designed at 5 Mtpa (Equinor, 2019).

Carbon neutral hydrogen, or hydrogen with a low carbon footprint often named "blue hydrogen" could be an important driver for CO_2 capture cost reductions and the development of CCS value chains. Air Liquide projects that the capture of CO_2 from its hydrogen units in Antwerp in connection to Northern Lights CCS initiative should contribute to accelerate the development of a hydrogen based and carbon free economy in Northern-Europe. Hydrogen will play a critical role in the decades to come in the shift towards a carbon free economy as it could be used for various applications in industry, power sector, residential sector or transport and mobility to effectively reduce CO_2 emissions.

In the Eemshaven area, Equinor is developing the H2M project concept for pre-combustion decarbonization of natural gas value chains by means of converting natural gas into hydrogen. Produced through Auto-Thermal Reforming (ATR) of natural gas, the hydrogen can be used for industrial processes, power production, domestic heat demand and transport. In order for the hydrogen to be low carbon, the CO_2 from the ATR process will need to be sequestered. Equinor is working on concepts where the CO_2 would be stored in the Northern Lights storage site. H2M project could achieve up to 2 Mtpa of CO_2 reduction from 2025 onwards.

In Dunkerque, ArcelorMittal is building a pilot plant to capture CO_2 by dedicated amines from the industrial blast furnace waste gas. The principle objective is to run the CO_2 capture plant fully on low temperature waste heat from the existing steelmaking processes. This way, the CO_2 capture will not be penalized by additional energy consumption. During the first phase, around 0,5 Mtpa of CO_2 will be captured by using waste heat. This CO_2 will be liquified and stored for transport. The amount of CO_2 can in the future increase significantly by a factor of 3 (Equinor, 2019).

2.6 Transport cost reduction potentials

Ship transport of CO_2 is preferred over pipeline transport when volumes are small and geographically far apart. The overall goal for Northern Lights is to gradually facilitate large scale deployment of CCS in Europe with a transport and storage network. Shipping would provide a strategic option as captured CO_2 volumes grow. Cross-border shipping will continue even when larger CO_2 volumes have enabled domestic and transboundary pipeline connections. The shipping solution will prove key for capture sites where dedicated CO_2 pipelines are not economically viable whether for size or geographical location. The Northern Lights project enables connections between elements of capture and storage initiatives which can act as an accelerator for further CO_2 capture projects (Equinor, 2019).

There is currently one main regulatory barrier that hinder cross border transport of CO_2 for storage. The definition of a CO_2 "transport network" in Directive 2009/31/EC currently excludes shipping, which makes it complicated to count CO_2 emissions shipped to storage as captured under the EU ETS rules (Equinor, 2019). The meeting between parties of the London Protocol during October 2019 passed a resolution to allow parties that have ratified the amendment to Article 6 to allow cross-border shipping of CO_2 for geological storage under the seabed to be provisionally applied.

2.6.1 Cost drivers transport

Pipeline costs are roughly proportional to distance. Pipeline costs consist mainly (normally more than 90%) of CAPEX, while shipping costs are less CAPEX-intensive (normally less than 50% of total annual costs). Due to high technical and commercial risk, the construction of a "point-to-point" offshore pipeline for a single demonstration project may be less attractive than ship transport.

Cost drivers for transport are

- CO_2-specifications, which vary for ships or pipelines
- Volumes: Pipeline costs are mainly determined by CAPEX (capital expenditure) and are roughly proportional to distance. They therefore benefit significantly from economies of scale and full capacity utilization.
- CO_2 ships have proportionally lower CAPEX than pipelines and a residual value if project terminates early, which significantly reduces the financial risk.
- Combining pipelines and ships for offshore networks could provide cost-effective and lower risk solutions, especially for the early developments of clusters.
- For large-scale transport infrastructure, long range and central planning can lead to significantly reduced long-term costs.
- Standardisation of ships. The NFSP has decided to initially use small and standardized ships with known technology to reduce risks.
- Spill-over learning effects from LNG and LPG-ships for large scale ship CO_2 transport
- Reduction of umbilical requirements and length.
- Reduction of interim storage volume and ship size based on logistic study, including reduction of jetty length and depth requirements
- Compression and liquefication as developed with higher efficiency.
- Design criteria for pressurized CO_2-transport, e.g. increasing the wall thickness of the pipe or by using steel of higher quality. Reliable simulations of CO_2 pipelines with new tools from R&D enables better optimization of material quality and material costs in addition to wall thickness.

2.6.2 NFSP transport cost reductions potentials

For the initial two Norwegian capture sites, purpose-designed fully pressurized ships with gross capacity of 7 500 m^3 of liquid CO_2 would be used. However, other ship sizes may be required to optimize the chains, depending on CO_2 volumes and distances from industrial sites in Europe. The captured CO_2 at Fortum Oslo Varme (FOV) will be liquefied on site and transported by lorry to the export quay in the Oslo harbor. This project will transport CO_2 by ship from harbor in liquefied form. The annual volume (0,4 Mtpa) to be transported from FOV corresponds to approximately 350 000 cubic meters of CO_2 at 6 bar and minus 55°C. For Norcem, the conditioned CO_2 will be transported in a pipeline from the production area to the storage tanks at the harbor, and from the tanks to the loading station, and then loaded onto ships.

The CO_2 will be offloaded at an onshore location on the west coast of Norway. At the offloading location Naturgassparken on the West Coast of Norway, CO_2 will be buffered in tanks, conditioned and sent by pipeline (approx. 110 km) offshore to a subsea template. Buffering the CO_2 in onshore intermediate storage tanks allows for continuous transport of CO_2 by pipeline to the subsea well for injection into a subsurface, geological storage complex. The CO_2 will be injected in the Aurora formation (south of the Troll field), a part of the geological structure Johansen, approximately 3 000 meters below the seabed. Equinor was awarded an exploitation permit for CO_2 storage in Aurora on 11 January 2019. From the Northern Lights onshore terminal, a pipeline would transport the liquid CO_2 to the subsea well(s) for injection and permanent storage.

Additional facilities for liquefaction and buffer storage of carbon dioxide will be required for potential further transportation of third-party CO_2 volumes from capture sites in Belgium, France, Germany, Ireland, the Netherlands, Sweden and the United Kingdom.

The figure below shows the Northern Lights transport and storage value chain overview.

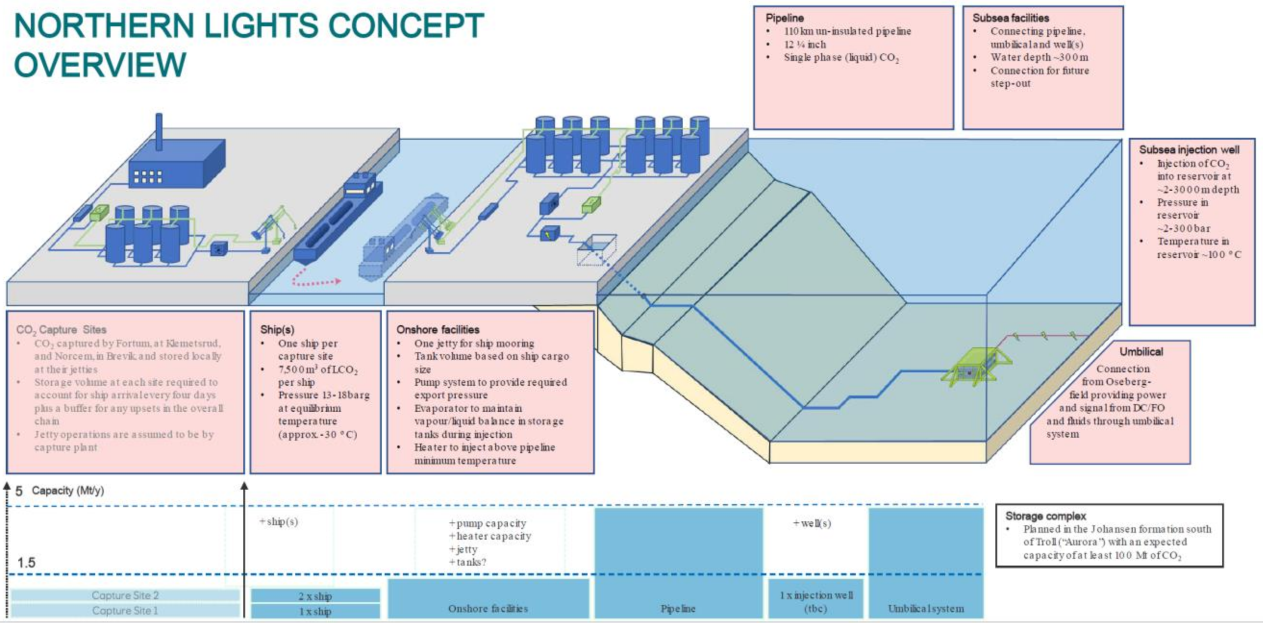

Figure 17 - Northern Lights Project Capacities and Technologies Value Chain Overview (Equinor, 2019)

Facilities for offloading CO_2 from ship to onshore terminal and for transport and injection of received CO_2 into the subsurface storage complex would include:

- Quay and offloading facilities for transferring liquid CO_2 from ships to onshore storage tanks
- Onshore storage tanks for intermediate storage of liquid CO_2
- Process systems required to bring the liquid CO_2 from storage conditions to injection conditions (pumps, heat exchangers, heating medium systems, etc.)
- Process systems required to vaporize CO_2 for return to storage tanks to replace volume of injected liquid
- Utility systems required to support the storage and injection facility

Control and monitoring facilities will be required for the operations of each part of the value chain in order to operate properly, securely and efficiently, including protection, monitoring and control systems.

The design basis capacities and strategy for future increase in capacity is outlined below for each part of the chain (Equinor, 2019).

- Ship: The strategy is to optimise number of ships for the initial volumes. Currently initial volumes include volumes from the two capture plants in the Norwegian demonstration project. One ship with a cargo size of 7,500m^3 is planned for each capture plant. Additional volumes will require additional ships.
- Onshore facility: The onshore processing equipment (pumps, heaters) is sized according to design basis of 1,5 Mtpa. Additional throughput will require additional capacity in processing equipment. Space and tie-in points for new equipment should be identified in the initial design.
- The onshore storage capacity is based on a ship cargo size of 7 500 m^3. Additional storage capacity could be required if ships with larger cargo sizes are introduced in the chain. Space for additional storage capacity has been secured.
- The import jetty is designed to receive ships of a size and frequency determined by the project. For future expansion, a new import jetty is required to allow for more, and potentially larger ships, or more frequent ship arrivals. A location for the future import jetty has been identified.
- Pipeline: The pipeline is designed to allow for a future flow rate of minimum 4 Mtpa based on a cost vs. benefit evaluation (actual capacity may be closer to 5 Mtpa for the selected storage complex).
- Subsea facilities: The strategy is to use satellite wells, with tie-in points for future tie-in of new pipeline extension to connect to additional satellite wells.
- Wells: The strategy is to drill a minimum number of wells for injection of CO_2. For future expansion, additional wells may be required depending on reservoir performance.
- Subsurface: The strategy is to select a storage location that allows storage of at least 100Mt CO_2.

Contrary to the case of pipeline transport, where the capital cost is the main driver, the operating costs make up the bulk of total cost for shipping. The key challenge, however, is to understand the constraints for each transport technology to reduce the over-design and associated costs, as well as where restrictions placed on the feed streams, for example purity may in some cases be relaxed to allow a reduced-cost whole-system design. Equinor is also investigating the possibility of using lower pressures for CO_2 ship transport at later stages to enable larger CO_2 carriers.

In addition, Equinor is evaluating how to set CO_2-specificiations for cost-effective utilization of different CCS chains. Necessary CO_2-specifications will vary from chain to chain. For example, a cost-effective CO_2-specification may differ for a ship-based chain compared to other transport technologies. The Norwegian CCS value chain project plan for a very pure CO_2-specification. Pipeline-based chains, like the Porthos CCS project, may possibly tolerate higher amounts of impurities. There are also other important CO_2-composition related factors that influence the cost-effectiveness of the CCS chain, such as the CO_2 source, capture and purification technology, safety and thermodynamic considerations, material integrity, etc.

Furthermore, Equinor is evaluating more radical cost cutting concepts (per ton) for a next value chain or from a large capture site, such as injecting CO_2 directly from ships offshore, omitting a necessary receiving terminal in the future. However, this results other types of challenges and could mean higher investments for interim tankfarms, development of load transmission technologies, and the need to verify new technologies. If the CO_2 would be injected directly by each CO_2 carrier, it would likely be batch-wise injection which could lead to additional strain on the equipment and reservoir. Another solution could be to have a floating CO_2 receiving ship at the wellhead, providing a buffer and thus enabling continuous CO_2 injection (Carbon Capture Journal, 2019). Further research and development will show how much the total net cost reduction potential with low pressure ships with direct injection may be.

The table below shows an overview of possible technology development projects for transport and storage defined within the Northern Lights project.

Table 4 - Possible technology development projects for transport and storage defined within the Northern Lights project (Equinor, 2019)

Discipline	Technology	Evaluation
Ship	Low temperature / low pressure	Low pressure ship tanks will be a key to reduce ship logistic cost having larger tanks and cargo onboard each ship. Multiple studies have concluded that operating close to the triple point is acceptable although no actual de-risking of the operational challenges has been performed. R&D in cooperation with SINTEF, partners carry out a work stream to conclude.
Subsea Production system	Electric valves	Avoiding hydraulic valves remove need for hydraulic lines in the umbilical. Project monitor an ongoing technology development program.
Subsea Production system	Subsea MEG tank	Subsea liquid, e.g. MEG, is needed for annulus management and valve testing. Only small volumes are needed. Subsea tank with pump system combined with electrified valves would remove all liquid lines in the umbilical. Solution has been presented by multiple suppliers, but not yet in use.
Interface	Metering	For future commercial CO_2 business, it may be required to perform in-line flowrate measurement for custody transfer rather than ship tank volume. Commercialized CO_2 ship transport will introduce multiple actors and the storage JV may require a local metering under JV control. The qualification of future metering is planned to take place at the Northern Lights facilities during operation.
Interface	OLGA Software	Ensuring liquid conditions during injection in all part of the system puts a restriction on operations. Low pressure reservoir conditions drive need for small tubing which puts an upper limit on the well maximum capacity. Knowledge and understanding of CO_2 behaviour in low pressure/high temperature conditions may release operative restrictions and flexibility. Improvement of the OLGA software is an ongoing work program where the operational experience from Northern Lights will be valuable.
Well	Downhole choke	Qualification of a downhole choking component may enable future batch CO_2 injection and ensure liquid flow conditions also in low-pressure reservoir.
Safety/ Process	Vessfire Software	Improvement of the Vessfire software to perform simulations of pressure release of vessels, loading/offloading operations. This work program aims to support increased understanding of CO_2 behaviour and associated risks
Safety	Software – analysis	Purpose to estimate consequence of CO_2 discharge subsea with dispersion analysis

The Northern Lights CO_2 ship transport solution would provide flexibility to collect CO_2 from multiple capture sites across Norway and Europe. The ship transport solution provides flexibility to reach large emission points in Europe, which would facilitate the scale-up of a CO_2 transport and storage network, open to CO_2 capture sites across Europe. (Equinor, 2019). Additional ships can be delivered relatively quickly, as it is possible with a «design one, build many» strategy before the volumes of CO_2 captured are high enough to make pipelines transport cost effective.

2.6.3 Technology development and roll-out cost reductions

The technologies for CO_2 transport are well established. There are >6500 km of CO_2 pipelines worldwide (both on-shore and off-shore), most of which are associated with EOR operation in the United States. The technology and rules for CO_2 transport with ships is also relatively mature with 5-6 relatively small ships transporting CO_2.

Whilst at small scale other options are available, the significant volumes of CO_2 requiring transport as a result of large-scale carbon capture means that only two methods are practical, pipelines and ship transport. The efficacy of either of these two depends to a great extent on the quantity of CO_2 and the distance from its point of capture to storage site; except over large distances (>1500 km) where it's expected that ship transport would be preferable, it is generally expected that the vast majority of transportation will occur via pipeline for full scale large volumes (Royal Society of Chemistry, 2018).

The interface between capture and transport begins usually with the compression and/or liquefaction of CO_2. During this process stage, the stream is transformed into a liquid or dense phase. The phase and amount of compression is determined based on cost considerations, the required flow rate, and the composition of the CO_2 stream. Cost-optimal design of a pipeline system, and to a lesser extent shipping, requires an understanding of the interaction between all of these factors (Royal Society of Chemistry, 2018).

2.7 Storage cost reduction potentials

CO_2 storage projects can be differentiated according to three factors related to costs: onshore is generally cheaper than offshore. qualification of storage in depleted oil and gas fields is generally cheaper and less time-consuming than qualification of storage in saline aquifers (SA), and cost savings can be achieved if legacy wells and infrastructure can be re-used. This study investigates offshore SA without re-using wells or infrastructure. Saline formations have been used for CO_2 storage in both onshore and offshore environments. Five large-scale CO_2 storage projects with storage in saline aquifers are currently in operation: Sleipner, Snøhvit, Quest, Gorgon and Illinois Industrial CCS project (large scale). The portfolio of large-scale projects is supplemented by a number of demonstration projects.

2.7.1 Cost drivers for storage

The major cost drivers are normally field capacity, injectivity, cost of liability, onshore or offshore location, well trajectory (vertical or deviated), MMV (in particular 3D seismic surveys), weighted average cost of capital (WACC), number of new observation wells and number of new exploration wells (IEA GHG, 2010).

The main factors that contribute to large differences in cost of storage are (IEA GHG, 2010):

- Field location (higher cost offshore than onshore, higher in Europe and Norway than other parts of the world)
- Field knowledge level (higher for depleted oil and gas fields than for SA implying need for more site characterization studies for SA compared to depleted oil and gas-fields prior to FID)
- Existence of reusable infrastructure (wells, offshore structure)
- Reservoir capacity (higher cost for smaller reservoirs)

- Reservoir quality (injectivity; higher cost for poorer quality reservoirs)
- Monitoring, Measurement and Verification (MMV) covers items that occur across the various phases of the storage lifecycle to monitor CO_2 migration and validate containment. Cost elements include:
    - Trade-off between using indirect measurements, such as seismic surveys, and direct measurements in wells.
    - Frequency of recurring MMV, such as logging, surface gas or seawater column monitoring, shallow zones monitoring, InSAR, gravimetry, induced microseismicity, etc.
    - The cost of drilling and instrumenting one or more monitoring wells if required, and costs of deploying permanent monitoring systems. Monitoring wells are more common onshore, and seldom drilled offshore due to high costs, and other MMV-tools are therefore prioritized.

The largest cost elements for CO_2 storage in SA are site characterization, drilling of injectors (plus platform/structure construction in the offshore case), operations and maintenance (IEA GHG, 2010).

Monitoring of CO_2 storage relies on a suite of technologies developed for petroleum production applications. Instrumentation in the well bores – down hole data includes pressure, temperature logging, fluid geochemical sampling, the use of tracers, near well geophysical saturation monitoring, and potentially cross well seismic reservoir characterization. Over large spatial scales, the use of seismic surveys has been demonstrated to be useful in monitoring the growth and migration of CO_2 plumes.

Field capacity has a high effect on costs for storage sites: cost sensitivities clearly show an economy of scale benefit: large storage reservoirs lead to a much lower cost per ton of CO_2 stored (up to 40%). Furthermore, injectivity is often an important contributor to variations in cost. For offshore cases, well completion costs are an important contributor to variations in cost, reflecting the specificities of that environment.

Finally, companies embarking on CO_2 storage will wish to make a profit, balanced against their risk, such as the industrial partners in Northern Lights. Such a profit has not been included as a cost element in this report since economical screening criteria will differ per company and also depends on the company perception of risk, as well as the fiscal framework.

2.7.2 NFSP storage cost reductions potentials

The Northern Lights project aims to deliver a permanent storage solution on the NCS with ample storage capacity beyond the Norwegian CO_2 sources and with facilities to offload CO_2 from ship. The chosen location for the receiving terminal for CO_2 is Naturgassparken (Natural Gas Park) in Øygarden municipality, west of Bergen. The pipeline from the onshore installations to the offshore storage site is estimated to be 110 km.

The Fortum Oslo Varme and the Norcem Brevik plant may provide 0,8 Mtpa of CO_2 combined. This would offer flexibility to include an additional 0.7 Mtpa of CO_2 from European sources in Phase 1, and an additional potential of 3,5 Mtpa in Phase 2. The total storage capacity in Northern Lights is estimated to be at least 100 Mt of CO_2. In order to reduce uncertainty in the subsurface storage capacity, project partners Equinor, Shell and Total are planning to drill a confirmation well in Q4 2019 (Equinor, 2019).

The Northern Lights project can allow CO_2 emitters in Europe to store their emissions without having to manage the risk and costs of qualifying individual storage locations. Shipping can be a preferred transport option for CO_2 sources located close to harbors, where no geological storage is available within reasonable distance, and may be achievable at a lower cost compared to pipeline transport for several potential CO_2 sources around the North Sea basin.

Monitoring of CO_2 storage relies on a suite of technologies developed for petroleum production applications. Instrumentation in the well bores – down hole data includes pressure, temperature logging, fluid geochemical sampling, the use of tracers, near well geophysical saturation monitoring, and potentially cross-well seismic reservoir characterization. Over large spatial scales, the use of seismic surveys has been demonstrated to be useful in monitoring the growth and migration of CO_2 plumes. The main challenge in the further development of these technologies concern their use in ways that allow for quantitative estimation the amount of CO_2 stored and the extent of the plume at the outer reaches of migration. This quantification is needed to verify the efficacy of storage. Leak detection and potential remediation actions to be implemented if CO_2 leakage occurs is a challenge for CO_2 storage with little analogue in the petroleum industry. Techniques can be used to monitor CO_2 concentrations or isotopic signatures in soil gas or the atmosphere over the site, or changes in other chemical signatures like pH (Royal Society of Chemistry, 2018).

Further development of monitoring instruments is required to enable quantitative predictions of, for instance, the amount of CO_2 stored, the extent of plume migration, and the extent of CO_2 trapping and dissolution. Although leak detection has not been a focus for the petroleum sector, leak detection technology is required to provide evidence that CO_2 is safely and permanently stored. Monitoring that can be performed to detect leakage, or verify the absence of leakage, includes pressure monitoring in selected indicator horizons overlying the formations into which CO_2 is injected, and measuring CO_2 flux at the surface over storage sites (either as CO_2 concentration in the soil/atmosphere or pH at the sea floor).

An atlas showing the potential for CO_2 storage under the parts of the Norwegian Continental Shelf that have been opened for petroleum activity was completed in the spring of 2014.The atlas shows great theoretical potential for CO_2 storage. The atlas is based on existing seismic data produced by the petroleum industry and describes storage conditions in both aquifer formations and decommissioned oil and gas fields. A similar CO_2 Storage Atlas has been developed by the British Geological Society. CO_2 stores in the UK waters are estimated to have 30% of Europe's CO_2 Storage capacity. The potential for storage around the North Sea, irrespective of the exact position of national boundaries, can help reduce costs for the large volumes of carbon sequestration required for European decarbonization (Equinor, 2019).

2.7.3 Technology development and roll-out for cost reductions

To understand the possible cost reductions, it is important to understand what storage options are available, both technically and politically. Not in my backyard is prominently in many countries, and SA is a wanted storage solution to test and learn.

The availability and capacity of suitable storage sites is a key consideration. Data were made available from the EU GeoCapacity Project database, comprising almost 1000 potential storage sites in deep saline aquifers (SA) and more than 1300 depleted oil and gas fields (DOGF) in Europe. As the bulk of storage capacity in Europe lies at depths of 1 500 m and below, the majority of CO_2 storage may take place at these depths. A depth of over 800 m is enough to ensure that the CO_2 is in a dense phase in the reservoir (IEA GHG, 2010).

Wells drilled into a CO_2 storage reservoir represent a potential risk for leakage. This goes for active wells in operation, as well as plugged and abandoned wells. Cement is the prime material used for mechanically stabilizing the wells and preventing leakage through them. CO_2 is a reactive and buoyant fluid that can, over time, degrade the cement. Thermal stresses arising during intermittent CO_2 injection may also be higher than in normal oil and gas operations and can impact well cement integrity. For CO_2 storage into a saline aquifer, wells are also plugged at maximum pressure (instead of after depletion, as in oil and gas wells). This can pose increased well integrity risk. A portfolio of research activities has resulted in knowledge and methods to better ensure well integrity, making it possible to avoid a significant share of maintenance costs, to reduce investments and thus, enable more safe and cost-efficient CCS.

Commercial transport and storage projects related to Northern Lights may enable further cost reductions. Some examples are Acorn (Scotland, UK), Teesside Cluster CCUS Project (UK) and Ervia (IE) projects. These projects would, if and when alternatives are needed, both provide alternative storage for Northern Lights' dedicated primary CO_2 capture sources and consider the Northern Lights as an option for storing their own CO_2 emissions. Such reciprocal arrangements for alternative CO_2 storage allow for CO_2 storage costs to be kept lower, and thus for volumes of CO_2 permanently stored in Europe to increase.

Reuse of existing infrastructure and establishing clusters and regions with a minimum of CCS-activity is key to lower costs. The North Sea Basin has many oil and gas producing assets that are approaching their final years of production. Some of these fields can be assessed further for CO_2 storage. Part of these assets (especially pipelines and wells, perhaps even platforms that would otherwise be decommissioned) could be reused if connected to a CO_2 transport network prior to decommissioning.

2.8 Product premium increase due to CCS

The additional cost for a low carbon or carbon neutral product or commodities such as steel or cement, or a kilowatt-hour of heat or electricity, may in some cases be low to insignificant for the end users, while higher for other products. In some cases, a low carbon or carbon neutral product could be well within the weekly or monthly fluctuations of commodities such as oil and gas.

For a power producer or energy intensive industry actor, CCS is first and foremost an enabler of more sustainable products with a lower carbon footprint. CCS comes with a certain investment and operational cost. However, these investments are expected to be necessary for maintaining a competitive industry, based on the assumption that in a carbon constrained world, there will be no room for industry emitting large amounts of greenhouse gases. Following this rationale, one might argue that CCS technologies is prerequisite for maintaining business in several industrial sectors, and that those who do not adapt will run out of business. Consequently, CCS technologies might form the foundation for very significant value creation in the future. This rationale, however, is based both on the assumption on large scale roll-out of CCS, and on the assumption that there will be no room for large CO_2 emitters (Størset, 2019).

Post-combustion capture is in many cases the only option to reduce CO_2 emissions from industrial processes, without redesigning the process. If the processes can be redesigned for easier capture from more pure CO_2 streams, the capture costs may be reduced further. The physical properties, composition and gas volume flows are different for each industrial process. Thus, the suitability and selection of a CCS technology would depend on these stream properties, for instance CO_2 concentration and moisture content. The challenge for the industrial sector will be maintaining international competitiveness with the implementation of technologies that reduce CO_2 emissions, but increase costs (Royal Society of Chemistry, 2018).

There are opportunities for receiving a premium for low-carbon cement, steel and other products. According to IEA, manufacturing costs for cement may be between 20-110 USD per ton cement, while it is 50-110 USD per ton iron and steel (IEA GHG, 2018). With a steel price of approximately 700 USD/ton, this means an increase of about 5-15%, while with a cement price of 120 USD/ton, an increase of more than 15%. When the CCS industry scale up, it is expected that the carbon neutral products will have a lower additional cost.

The first step to creating market for low carbon products is to supply selected markets, with a higher willingness to pay, the first low carbon products. One such a sector is the building sector in the Nordics where there has been established a market for low carbon concrete for sustainable certified buildings (e.g. BREEAM, DGBN, WELL and LEED). Public procurement is also looking for low or emission free concrete for roads and bridges, and are in some cases willing to pay the extra few percent as a premium to get the low or zero carbon products.

3 CONCLUSIONS AND FINDINGS

This report investigates the potential cost per ton reductions for stored carbon dioxide for The Norwegian Full-Scale CCS Demonstration Project (NFSP). The analysis indicates that a complete demonstration value chain will bring costs down through specific contributions to the technology and supply chain development of each part of the project. However, as the report discusses in detail the cost reductions will not be equally significant throughout the chain and the cost reductions are strongly linked to further capacity increase. Therefore, the analysis also estimates how the NFSP-project contributes to cost reductions for future CCS projects with increased capture, transport and storage capacity.

The analyses show that the demonstration effect by the Norwegian Full-Scale CCS Demonstration Project may contribute to cost reductions due to:

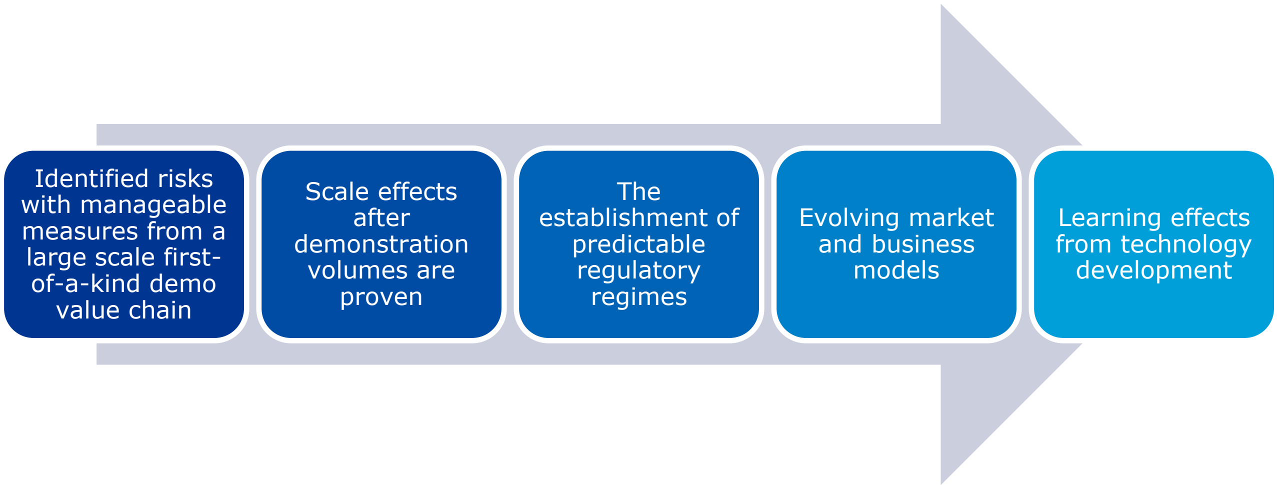

Figure 18 - Demonstration effects and cost reductions

High specific costs are expected when configuring a new demonstration value chain which focus on learning and technology development rather than optimizing for the lowest specific cost. The high specific cost per metric ton is first of all due to the designed overcapacity for parts of the value chain. In addition, the cost levels are affected by the long distances from the capture site to the storage reservoir, small initial capture volumes, ship transport and an onshore terminal. Utilizing the flexibility with ships for various demonstration capture volumes, other than the Norcem Brevik and Fortum Oslo Varme volumes, is important to reduce risk and enable various demonstration and pilot volumes.

The capture costs contribute to a high share of the value chain cost. For the Norwegian Full-Scale CCS Demonstration Project, the capture investments and operational costs are more than half of the total costs. The capture cost represented in the following are representative cost levels and the most realistic current estimates for capture from cement production and waste-to-energy plants. The cost per ton will decrease significantly when the value chain capacity is fully utilized from 0,8 to 5 million tons per annum (Mtpa).

The costs and cost reductions are estimated in stages to show the effect of various assumptions from increased utilization, optimization and wide industrial development. This will not be the case in the real world, where the various scale, optimization and learning effects will all gradually evolve together to provide cost reductions. The costs are both estimated with an investor perspective and according to the Norwegian Environment Agency method (NEA). One key difference is the rate of return, 8% for investors and 4% for the NEA-perspective. The other and most important difference is that emissions for the investor perspective are discounted. The effect of these different calculation methods, with equal investment and operational costs, is that the NEA method shows values half the amount of the investor's perspective. The NEA calculations are only used to compare climate measures across industries. The specific costs are given as net present costs in Norwegian Krone, NOK per ton stored CO_2 with a time horizon of 25 years. The table below shows the 2018 investment and operational cost estimates from the industry partners, with the estimated costs per ton with two methods of calculation.

Table 5 – Investment and operational costs for The Norwegian CCS Demonstration Project

CCS value chain steps	Investments (CAPEX, constant 2018)	Operational costs (OPEX, yearly constant 2018)	Net Present Costs *«Investor»* ($NPC_{INV, 25\ years, 8\%, DCE}$)	Net Present Costs *Norwegian Environment Agency* ($NPC_{NEA, 25\ years, 4\%}$)
Capture Norcem (0,4 Mtpa)	3 097 MNOK	120 MNOK	1 085 NOK/ton	419 NOK/ton
Capture FOV (0,4 Mtpa)	4 715 MNOK	239 MNOK	1 810 NOK/ton	713 NOK/ton
Ship transport (two ships, 0,8 Mtpa)	929 MNOK	84 MNOK	218 NOK/ton	92 NOK/ton
Storage (0,8 Mtpa)	5 475 MNOK	167 MNOK	920 NOK/ton	344 NOK/ton
Total (0,8 Mtpa)	**14 216 MNOK**	**610 MNOK**	**2 585 NOK/ton**	**1 002 NOK/ton**

The cost of capture at FOV with an investor's perspective is calculated to be 1 810 NOK/ton based on DG 2.0 data (Fortum, 2019). Norcem on the other hand, have a calculated cost of 1 085 NOK/ton (Norcem, 2019). The difference in costs are mainly due to lower CO_2-concentrations in the combustion fumes at Fortum compared to Norcem which require larger capture systems, that Norcem has free waste energy from the cement process for running the capture process, location specific costs and that FOV has truck-transport to Oslo harbor, FOV capture high shares of the CO_2 from the flue gases, and has lower and variable CO_2-rates due to the combustion of various domestic household waste. Some of the reasons for the high capture costs at both sites are mainly the integration costs, low volumes which give high specific costs (few economies of scale) and temporary storage for the ship transport downstream. However, the costs may have been even higher with full capture. At the two sites about 50 % of the emissions are captured in a partial capture process. Costs can become exponentially higher for the same plant if >50 % of emissions must be captured.

Figure 19 and Figure 20 shows possible cost reductions from the increased utilization and proposed optimization of the value chain, and a possible CCS industry development. The stages from 0 to 2 show the average cost per ton for the NFSP as the volumes increase from 0,8 to 5 Mtpa. Stages 3 and 4 show cost reductions as a result of second-generation optimized capture sites. This concept includes pipeline transport instead of transport by ships. Such a transport concept with pipeline will typically be from a cluster with several point emissions, and a pipeline directly to the well and storage site. From this point on, industry learning curves are projected to show expected learning rates and cost reductions as the accumulated capacity increases. It is worth noting, that other CCS value chains may have completely other cost levels, due to other locations and other technologies. It is also important to understand the calculation method, which may vary from project to project.

The stage 4 scenario requires large clusters of CO_2 capture sites in relative proximity to the shore and offshore storage as well as huge investments. At the present this does not seem realistic given the availability of capture sites and the maturity of the technology. These kinds of future clusters and value chains are enabled by projects such as NFSP. Stage 4 reflects one possible optimization of the NFSP value chain, onwards from this point we apply industry learning curves that show expected learning rates and cost reductions as the accumulated capacity increases.

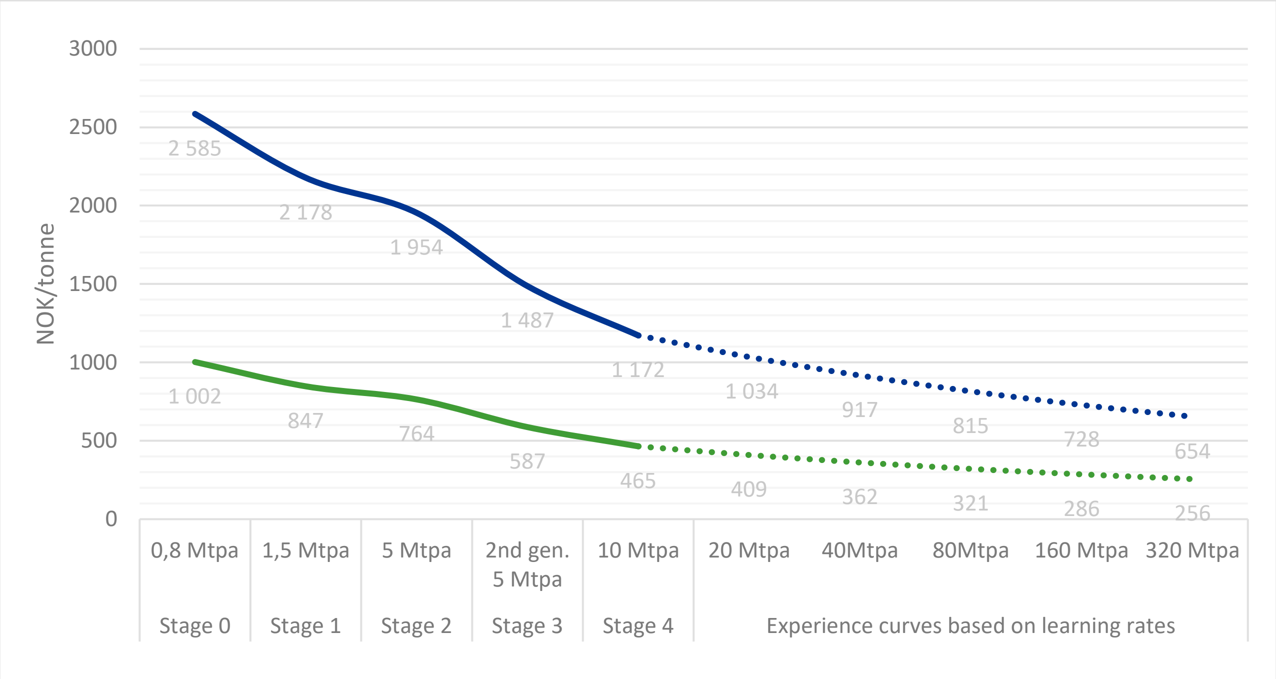

Figure 19 - Cost reductions estimates from capacity utilization increase, optimization and learning for increased CCS capacity. Investors perspective (high curve) and Norwegian Environment Agency method (low curve)

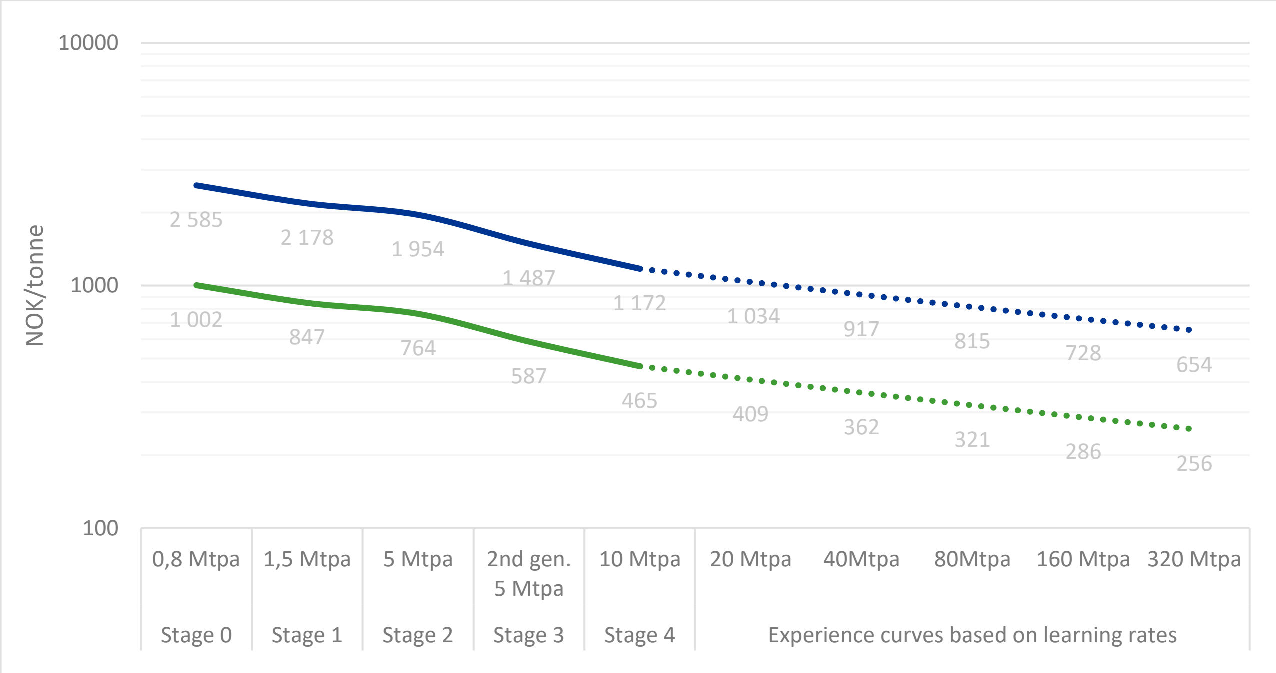

Figure 20 - Cost reductions estimates logarithmic scale, from capacity utilization increase, optimization and learning for increased CCS capacity. Investors perspective (high curve) and Norwegian Environment Agency method (low curve)

3.1 Expected cost reductions calculated by the Norwegian Environment Agency method

The cost estimates are based on the cost data from the industry partner decision gate 2.0 (2018) concept reports, provided by Norcem Brevik, Fortum Oslo Varme and Equinor. The recommended method provided by The Norwegian Environment Agency is used for comparing carbon abatement measures from various sectors and cannot be compared directly with the EU ETS quota price.

The NEA costs for the NFSP with 0,4 million tons per annum (Mtpa) captured from Fortum Oslo Varme (FOV) and transport and storage, is estimated to be just under 1 500 NOK per ton. If the value chain is fully utilized with 5 Mtpa capacity, with the same capture cost levels as FOV, the costs are estimated to be reduced by approximately 40% to 910 NOK per ton. The costs for the NFSP with 0,4 Mtpa capture from Norcem and transport and storage, is estimated to be 1 200 NOK per ton. If the value chain is fully utilized with 5 Mtpa capacity, with the same capture cost levels as Norcem, the costs are estimated to be reduced by approximately 49% to 620 NOK per ton.

This demonstration value chain may contribute to identify cost reductions for future and similar value chains. This is due to introducing improved or new technologies and the optimization of the value chain. The analyses estimate that future similar value chains will have a cost level of just under 500 NOK per ton if the capacities increase three times. With a wide implementation of CCS internationally and accumulated capacity exceeding 1000 Mtpa in line with reaching ambitious climate targets, the analyses show cost levels down towards 250 NOK per ton. In addition to the Norcem Brevik and Fortum Oslo Varme captured volumes, third party capture volumes may be part of the value chain. With volumes from Norwegian clusters and the North-European process industry there may be opportunities to reduce the average value chain cost with increased volumes.

The discount rate for the NEA calculation method is given and changing the rate gives some peculiar effects since emissions are not discounted. The effect is that the cost decreases with increasing discount rate(!). For these reasons performing a sensitivity analysis on the discount rate makes little sense. The expected lifetime for the investment is an important assumption however and both increased and decreased lifetime has a significant effect on the estimated cost per ton as the graph below illustrates. The baseline assumption is shown by the dark blue line, with 25 years lifetime. If the lifetime is increased to 35 years, the associated drop in cost per ton is estimated to just over 20%. The cost per ton increases with almost 50% if the lifetime is reduced to 15 years.

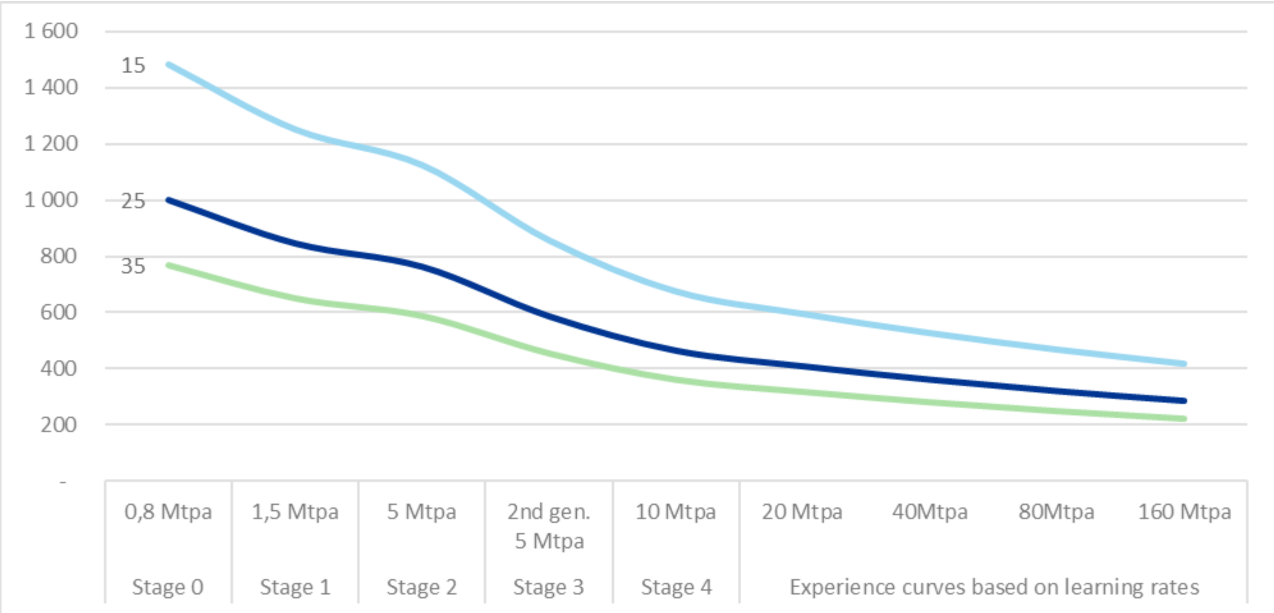

Figure 21 – Cost reductions with lifetime sensitivities of 15-35 years (NEA Method)

3.2 Expected cost reductions with an investor's perspective

In this report, the real discount rate before tax is set to 8% for private investors. This rate of return is comparable to the average real rate of return before tax on the Oslo Stock Exchange. The required rate of return for CCS investments may be lower after some time with lowered technological, regulatory and commercial risk for CCS-projects or in periods with abundant capital (low cost of capital). There are discussions regarding the regulation of the storage and transport infrastructure of the value chain, and whether it will be able to attract capital with lower required rate of return.

The costs for the NFSP value chain with an investor perspective for 0,4 Mtpa captured CO_2 from Fortum Oslo Varme, and transport with ships and storage in the Aurora storage complex, is estimated to 3 870 NOK per ton. If the value chain is fully utilized with 5 Mtpa capacity, and the same capture cost levels as FOV, the costs are estimated to be reduced by 40% to approximately 2 300 NOK per ton.

The costs for the NFSP value chain with an investor perspective for 0,4 Mtpa captured CO_2 from Norcem, and transport with ships and storage at the Aurora formation, is estimated to 3 150 NOK per ton. If the value chain is fully utilized with 5 Mtpa capacity, and the same capture cost levels as Norcem, the costs are estimated to be reduced by approximately 50% to 1 600 NOK per ton.

It is expected that there will be cost reductions for future and similar value chains (consisting of cement and waste-to-energy capture sites) due to introducing improved or new technologies and the optimization of the value chain. The analyses estimate that future similar value chains will have a cost level of 1 200 NOK per ton. With a wide implementation of CCS internationally and accumulated capacities exceeding 1 000 Mtpa (in line with reaching ambitious climate targets), the analyses show cost levels developing towards 500 NOK per ton. The technology development may be compared to historical development of oil and gas refinery technologies, LPG and LNG transport with ships, sulfuric (SO_x) and nitric (NO_x) cleaning.

Private investors typically require a higher rate of return than the public sector. This is especially true for projects with a high degree of uncertainty. Additionally, private investors will discount the emissions reductions as monetary values since their income from the project will come from the emission reductions. The emissions will have a monetary value that is directly related to EU ETS prices and it could also have a monetary value through the increased premium the industry actors can place on their product price. The calculated cost per ton with an investor's perspective is therefore directly comparable with the EU ETS price. Investments in CCS will be profitable when the cost per ton is equal to or lower than the price of CO_2. If the reduction in emissions has some other value to the investor, e.g. a premium price on low or CO_2 free products, this breaking point will be reached before the costs of CCS falls below the ETS price.

The costs from an investors perspective is sensitive for the required rate of return and, to a certain degree, the life expectancy of the investment. The base case that is used throughout this analysis is 8% real return rate before tax and 25 years life of the investment. The graphs below show a sensitivity analysis for both these input variables. If the required rate of return (cost of capital) is lowered to 4% (from 8%) this corresponds to a 25% reduction in cost per ton. The investor perspective is much less sensitive to increased lifetime of the investment. This is due to heavy discounting of the effects at the end of the lifetime of the investment.

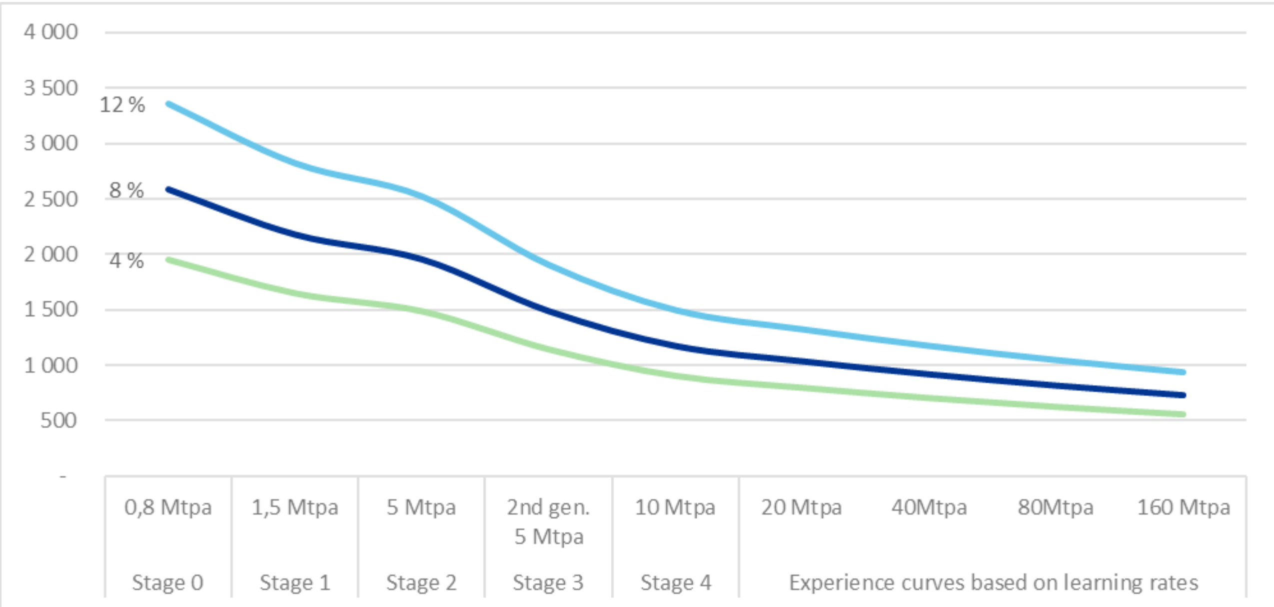

Figure 22 - Cost reductions with rate of return sensitivities, investor's perspective

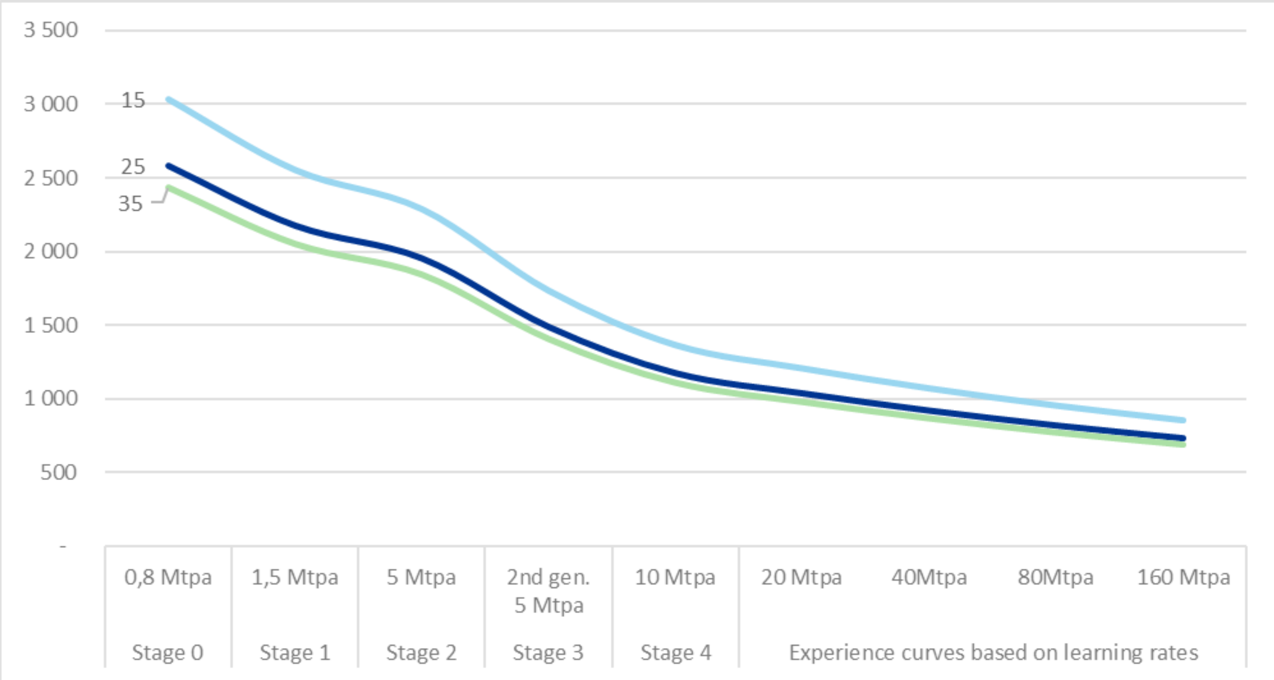

Figure 23 - Cost reductions with lifetime sensitivities, investors perspective

3.3 The NFSP as an enabler for further CCS cost reductions

The cost reduction potentials due to removal of barriers due to regulation and legislation is also an important factor which is not easy to quantify. By realizing the capture projects important learning will be achieved. The learnings will be related to the realization and operations of capture plants integrated with industrial processes, regulation of the whole CCS value chain, establishing business models for capture, transport and storage, updated CCS-costs and the possible future development of CCS-technologies (OED, 2016).

The realization of NFSP is expected to contribute to the following learning effects (Gassnova SF, 2015)

- Trust in and general knowledge on CCS as a climate measure (from society and the industries involved)
- Reduced financing and insurance costs for upcoming projects
- Learning from directly involved partners and subcontractors
- Clarifications of regulatory matters such as ETS, storage and emission regulations
- Establishment of roles and demonstration of business model
- Clarification of interface problems and possible learning related to technological whole chain challenges
- Solving technological challenges and optimization of individual components on a large scale
- CCS chain where industrial players, transport operators, oil companies and the state have found a suitable form of cooperation. This learning has special transfer value to CCS projects, where an operator is not able to handle the entire CCS chain.

- Conditions related to the quota system. Learning will be relevant to the EU energy and industrial sectors, as well as European government agencies, for upcoming CCS projects in the EU

This demonstration project is in many aspects a first-of-a-kind value chain with a unique setup of capture from cement and waste-to-energy and ship transport. Some of the technologies such as pipeline transport offshore and saline aquifer storage are technologically mature and have been demonstrated on a large scale previously. However, the project has third party access which may enable a whole range of industries to enter the CCS value chain. Because of this, the value chain may enable and kick start a way forward for industrial, commercial, regulatory and technical learning that will bring the costs of CCS further down. Without a demonstration project these cost reductions will be postponed and delayed until another demonstration project eventually would be realized.

The figure below sums up important tasks for how to further develop the CCS-industry. The NFSP is one small step on the development of a whole new industry, which builds on much existing knowledge, but also has to find new solutions to reach cost reductions.

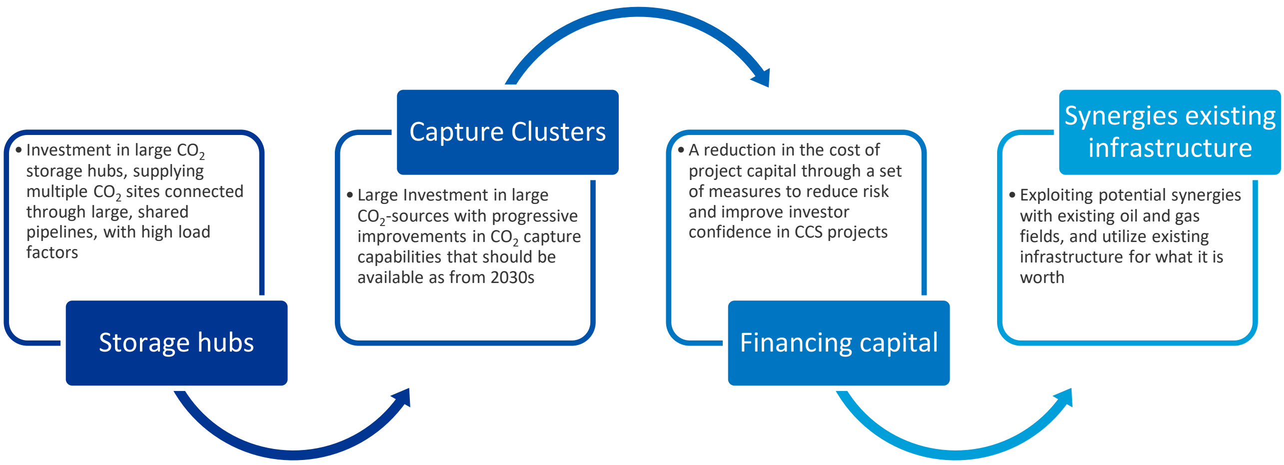

Figure 24 - The following overarching measures can contribute to even further cost reductions for the CCS industry

The long-term development towards an established CCS-industry will depend on the development of large-scale demonstration projects. The Norwegian Full-Scale CCS Demonstration Project, with the two capture sites at Fortum Oslo Varme and Norcem Brevik and the transport and storage infrastructure represented by Northern Lights, is important for this development.

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5 ATTACHMENTS

5.1 Contents of each chapter

5.1.1 Chapter 1 - The Carbon Capture and Storage Value Chain

Chapter 2 includes a short introduction covering the background, purpose, mandate and scope for the Norwegian Full-Scale CCS Demonstration Project (NFSP) and the cost reduction analysis. Further, it contains a description of the historic timeline and process for developing the NFSP. The CCS chain for the NFSP is described in more detail, how it is unique compared to other CCS chains, and what elements of the chain contributes most significantly to the relatively high specific net present costs.

The final part of the chapter reviews the status of the CO_2-market globally and outlines how the NSFP will be an important part of developing the CCS industry towards a competitive and commercial industry.

5.1.2 Chapter 2 - Potential for cost reductions

Chapter 3 describes the methodology for calculating the net present costs and possible cost reductions. Further, cost drivers for capture, transport and storage are explained in general. More detailed reviews of cost reduction potential from increased utilization of the value chain are provided. This is followed by cost reduction estimates for an optimized value chain, and a wide CCS deployment.

Finally, the chapter discusses how not only cost reductions and EU ETS may finance CCS, but how carbon neutral or green end-products with small premiums may cover the CCS value chain costs.

5.1.3 Chapter 3 – Results and Conclusions

Chapter 4 presents the results and concludes on possible cost reductions.

5.1.4 Attachments

The attachments contain references, detailed descriptions on the methodology, benefit realization and project information.

5.1.5 Not included in the report

The report analyses the technologies chosen by the industry partners and Gassnova, with a general view on other technologies and solutions. We have not performed detailed analyses for technology shifts. Other storage solutions than geological storage in saline aquifers are not considered, which means that costs for geological storage in depleted oil or gas fields or geological storage through CO_2 injection for enhanced oil recovery (EOR) is not evaluated, even though these mechanisms may contribute to reduced costs and economically profitable business cases. However, EOR is in many cases not considered a climate measure with net volumes for storage. In the US storage through EOR is eligible for credits and it is also not excluded for credits under the CDM. The NFSP and Gassnova mandate explains in further detail the reason for technology choices and the value chain design.

5.2 Abbreviations

ATR – Auto-Thermal Reforming of natural gas

CCS – Carbon, Capture and Storage (includes transport from the capture to the storage site)

CDM – Clean Development Mechanism

CRI – Commercial Readiness Index

DOGF – Depleted oil and gas fields

EOR – Enhanced Oil Recovery

FOV – Fortum Oslo Varme, the joint-venture waste-to-energy plant owned by Fortum and Oslo Municipality, located at Klemetsrud, south-east Oslo

LR – Learning Rate

Mtpa – Million tons per annum

NB – Norcem Brevik, the cement production CO_2-capture site

NEA – Norwegian Environment Agency method

NFSP – Norwegian Full-Scale Demonstration Project

SMR – Steam Methane Reforming

SA – Saline Aquifers

TRL – Technology Readiness Level

5.3 Background and purpose

The Granavolden declaration says that the Norwegian Government will contribute to develop technology for CO_2 capture, transport and storage, and has an ambition to realize a cost-effective full-scale CCS demonstration project in Norway, given that this will give technology development in an international perspective[2]. The government's long-term objective for the NFSP is in line with this declaration and states that Norway shall *«contribute to the development of CCS in a cost effectively manner, in order to reach long term climate goals in Norway and EU»*. Based on this the project goals and end-state objectives are:

- Demonstrate that CCS is feasible and safe
- Reduce cost for coming CCS projects through learning curve effects and economy of scale
- Give learnings related to regulating and incentivizing CCS activities
- Contribute to new industrial opportunities

The state enterprise Gassnova manages and coordinates the NFSP and oversees the benefit realization. However, the industry is actively developing the solutions. Norcem Brevik, Fortum Oslo Varme and Northern Lights (Equinor, Shell and Total) have developed their projects in line with the project's goals

[2] Unofficial translation

and framework, and with their own perspective and industrial opportunities. The projects have matured over time, in line with other large industrial projects. During this process the overall project and each industrial players' project has been detailed, leading to the documentation the Norwegian parliament will receive for the final investment decision.

This means that Gassnova monitors the industrial partners Norcem Brevik, Fortum Oslo Varme and Equinor, Shell and Total with the Northern Lights project. Gassnova evaluates the engineering and design studies at the end of each study phase. Gassnova will also ensure optimization of the entire CO_2 management chain.

5.4 Technical, market and regulatory learning

The figure below shows a model for learning and experience sharing within the industry, for both production costs, producer prices and the market prices. This model focus much on the technical development, but addition to the industry learning, the regulatory and judicial learning is crucial when establishing a new industry such as CCS.

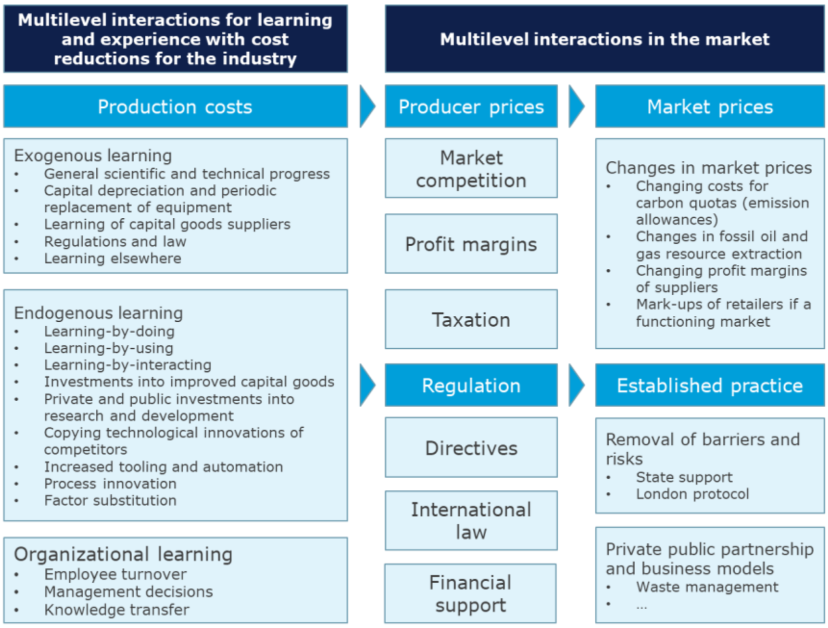


Figure 25 – Learning and experience for technical, market and regulatory development (DNV GL, 2019)

5.5 Methodology details

Comparing CCS costs is challenging due to the wide range of methodologies and assumptions that are used. Also a lack of real empirical data (currently, in the power sector there are only two full scale CCS plants in operation), difficulty in choosing the baseline when comparing different CCS plants and locations, a variety of currencies and currency base years in the reported literature, cost differences due to unavailability of transport and storage infrastructure and a variety of processes, operating conditions and capture processes contributes to this. The strength of the data and analysis presented here is that with the concept and Front-End Engineering and Design FEED DG 2.0 data from the Norwegian value chain, we have concrete, complete, specific and transparent data to work with.

The definition of a full-scale CCS project varies by industry and projects. The full-scale definition by the Global CCS institute is capture of 1 Mtpa from coal power plants and 0,5 Mtpa capture from gas power plants and industrial sites.

5.5.1 Cost of CO_2 stored vs cost of CO_2 avoided

Since energy is used and CO_2 is emitted to capture, transport and store the CO_2, stored CO_2 will for most carbon capture and storage projects be less than the amount of carbon avoided. The cost of carbon avoided is a very complex calculation since the carbon emissions from the value chain are already partly paid for through CO_2 emission taxes. Another major complicator for this project is the fact that much of the carbon that is burned, especially at Fortum Oslo Varme, is biogenic. This means that the project is actually reducing the amount of CO_2 in the atmosphere by capturing the emissions. Since a significant part of the CO_2 is biogenetic the amount of CO_2 avoided could be even higher than the amount of carbon stored. To keep this analysis as transparent and simple as possible we have focused on the easier to understand calculations for cost of carbon stored, even though this is not fully in line with the guidelines developed by the Norwegian Environmental Agency (see further details below). Due to the high share of Biogenetic emissions this is however more likely to be a conservative approach.

5.5.2 Net present value of Cost of stored CO_2

The net present value method makes it possible to compare benefits and/or cost effects which happens at different points in time. Estimated effects are discounted to the same point in time by using a discount rate. The use of a discount rate reflects that future benefits and costs is not valued as high as benefits and costs today and that capital has an alternative use.

The discount rate is a chosen parameter which may be interpreted as a minimum rate of return, which reflects the valuation of money or benefits today in comparison by a day in the future, set by the decision maker. Alternatively, or in addition, the rate can be based on other investments and/or the cost of capital adjusted for risk. The discount rate can therefore also be considered as the opportunity cost, i.e. the best alternative use of that capital. Therefore, what is the correct discount rate for a given investment will depend individually on preferences, capital access, risk aversion and access to alternative investments.

$$CAC_{INV} = \frac{NPV_{CCS}}{\sum_i \frac{\dot{M}_{CO_2,stored,i}}{(1+r)^i}}$$

Guidance from the Ministry of Finance for socio-economic (cost-benefit) analyzes with the regards to the use of calculation rates:

According to the Ministry of Finance circular paper R-109/2014, a discount rate of 4% should be used for effects for the first 40 years of the time period for the analysis. If the time horizon extends beyond 40 years, the rate should be 3 % up to 75 years, and 2 % for the remaining years. The Directorate for Financial Management's guide to socio-economic analysis states that this is a real interest rate. It is thus real values that must be discounted at this interest rate and not nominal price-adjusted values.

The Norwegian Environment Agency guide for calculating the cost of CO_2-measures

In its updated guide for calculating the cost of measures for CO_2 reductions[3], the Norwegian Environment Agency recommends that the net present value method should be used when calculating the cost of measures for CO_2 reductions. More specifically, they recommend that the following fraction be used to calculate the CO_2-cost:

[3] Metodikk for tiltaksanalyser, M-1084 | 2019 – OPPDATERT VERSJON - APRIL 2019

the net present value of the total socio-economic cost from the base year to the end of the measure,
divided by,
the sum of total CO_2 equivalents (not discounted) reduced from the base year to the end of the lifetime of the investment.

$$CAC_{NEA} = \frac{NPV_{CCS}}{\sum_i \dot{M}_{CO_2,avoided,i}}$$

Note that for this report we have used the amount of CO_2 stored and not avoided. See chapter 5.4.1 for more details. The cost side only includes direct investment costs. Tax financing costs or other costs have not been included.

In the referenced paper, The Norwegian Environmental Agency concludes that this equation is easier to understand and communicate compared to previously used methods. NEA also refers to studies that Enova has performed where they have reviewed different calculation methods for determining the cost of climate investments. In addition, NEA states that the same method is used in several of North European countries. Both Sweden and Denmark use this equation in their measures and policy assessments. It is a significant advantage that the calculation method is standardized so that cost figures are comparable between projects.

DNV GL's assessment of the calculation method for the cost of measures

The net present value method is an established investment analysis tool. It will, with transparent assumptions, give a good foundation for evaluating how attractive an investment is. The NEA equation treats the benefits (CO_2-reduction) and the cost side (investments and operational costs) differently since only the cost side is discounted.

By using NEA calculation method, the income from the investment (reduced CO_2 emissions) is given a higher weight than the cost of the investment (CAPEX and OPEX) since only the latter is discounted. A discount rate of 4% is also lower than what a commercial investor normally would require for a project with the same risk profile. The NEA method therefore underestimates the costs and overestimates the benefit from an investor perspective. The cost per ton calculated with the NEA method does not reflect the price per ton an investor would require using as a decision for an investment.

The cost per ton calculated using the Environmental Agency method is therefore not relevant to compare with the CO_2-quota price.

Conclusion on calculation method

One important thing to consider when choosing calculation method is if the data can be compared with the cost of other climate mitigation measures. Another important perspective is to calculate a cost measure that is relevant for a commercial investor and that is comparable to the co_2 quota price.

Both these considerations cannot be met by using only one of the calculation methods described above. To satisfy both we will use two calculation methods that will give very different costs per ton.

First, we will use the calculation method specified by the Norwegian Environmental Agency as described in the previous chapter.

The other calculation will be based on the commercial method with a higher discount rate, where also the benefit side is discounted with the same discount rate as the costs. This calculated measure cost can be compared with the ETS quota price, and therefore give relevant information regarding how much the costs must be reduced before it can be financed by quota costs only (within the sectors subject to quotas). With other words, how much must the measure cost be reduced, before the quota cost by itself is enough to finance the carbon capture, transport and storage.

In this report, we have used a real discount rate before tax of 8% for the investors perspective. This is comparable to the average return on the Oslo stock exchange before tax, adjusted for inflation. The rate is also well in line with discount rates used in other studies mapped studies where a discount rate between 7 and 14% has been used (Hassan, 2019). In these studies, it is not specified whether a real or nominal discount rate has been used and whether the discount rate is before or after tax.

We have stated specifically which method has been used throughout this report and provided both perspectives for all cost per ton estimates.

5.5.3 Cost model – Cost Breakdown Structure

The industry participants have provided detailed cost estimates within a cost breakdown structure (CBS). These estimates have been used for estimating possible cost reduction curves based on future economies of scale, optimization of the value chain and possible technology development.

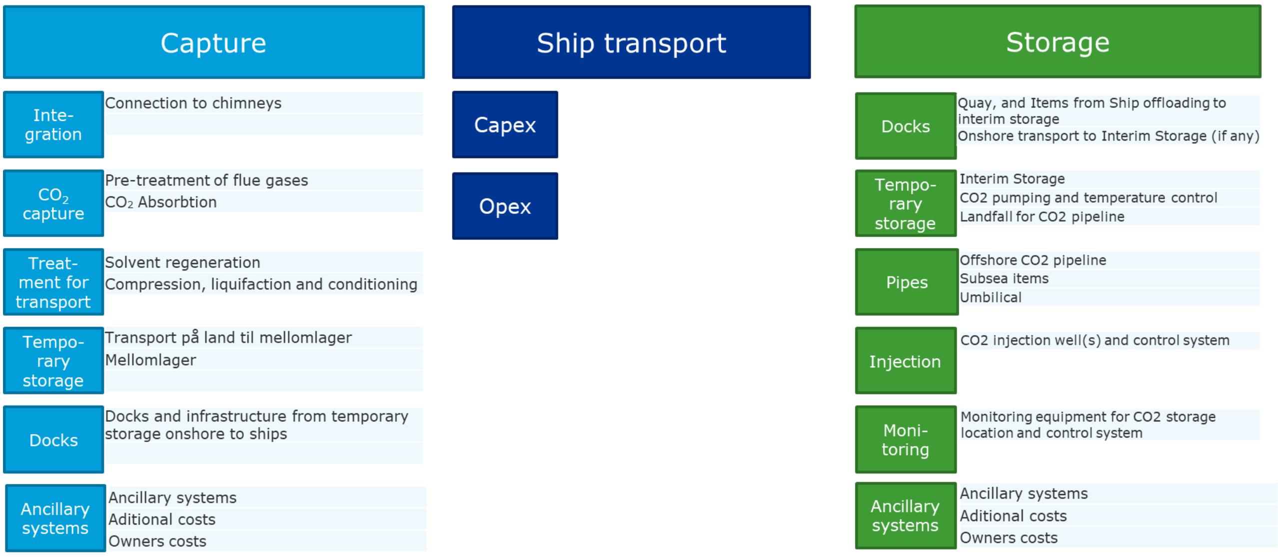
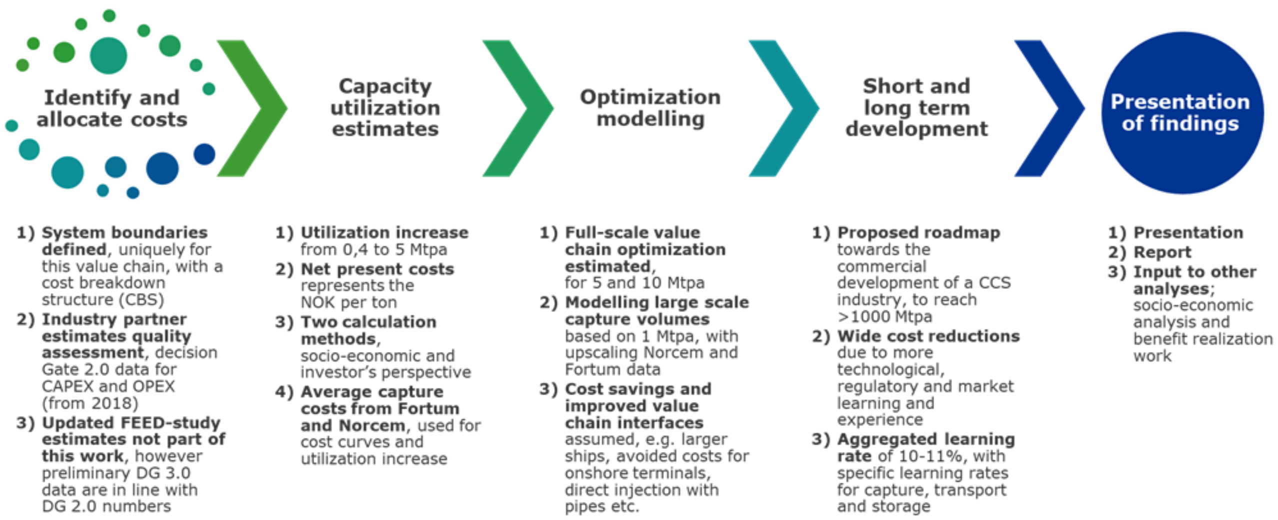


Figure 26 – Cost Breakdown Structure (CBS) as provided by Gassnova

The overall process and method have followed these steps:



5.5.4 Assumptions

This report focuses on CO_2 capture, transport and storage for the sake of CO_2 stored and includes only storage within saline aquifers (SA). The business case for CO_2 stored is quite different to that of CO_2 EOR. Depleted oil and gas fields (DOGF) CO_2-storage is a viable storage solution, with potential lower costs, but not calculated here. Reuse of wells ("legacy wells") and equipment may save costs even further.

The oil and gas industry generally assume a learning rate in the order of 3% for operating costs (IEA GHG, 2010). We have estimated an aggregated learning rate of 10% with a learning rate of 15% for capture, 2% for transport and 3% for storage. This aggregated learning rate has been used for the experience curve modelling for the stages after maximum capacity utilization of 5 Mtpa with a new generation of value chain of 5 and 10 Mtpa.

When comparing cases of cost reduction estimates, CCS is modelled as a lump-sum add-on cost to the technology it is combined with, while other models separate capture costs and transport & storage and a few separate all cost items. The latter modes obviously give more detail about the CCS supply chain, which enables modelers to also test the sensitivity of results to individual cost components. There is quite a divergence with respect to the assumption about CCS lifetimes, ranging from 30 to 60 years (partially depending on the technology), though most of the models assume around 40 years. (Royal Society of Chemistry, 2018).

Not included in the analysis:

- Increased emissions from the CCS activity itself, and effect of capture of biogenic CO_2
- Tax effects
- Indirect costs and tax financing costs (social economic costs other than direct investment costs)
- Residual values or decommissioning costs

5.6 Process and involved parties

5.6.1 Process and timeline

The process has consisted of a review of the concept-study data from the industry participants, discussions with Gassnova experts, workshops, a review of documentation from the industry partners (e.g. lessons learned reports, memos on Value improvement Projects) as well as industry reports as specified in the reference list.

There has been put a lot of effort to explain the atypical aspects of the Norwegian Value Chain demonstration project, compared to a likely and typical future large-scale value chain, and how the NFSP will contribute to learning effects. An important part of the project has been to identify the value chain base case with four additional stages, and the roll-out of future CCS projects. The project has received input on possible CCS roadmaps and cost reductions for each of the value chain parts, based on CCS experts from Gassnova, DNV GL and Equinor.

The figure below shows the project timeline.

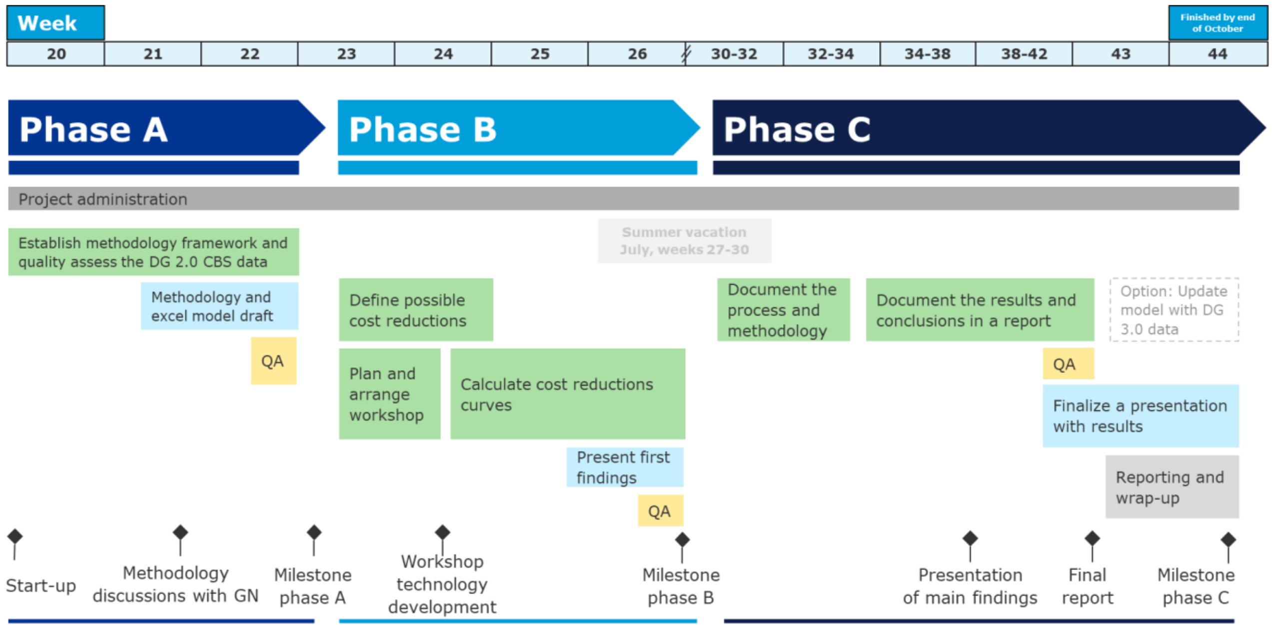
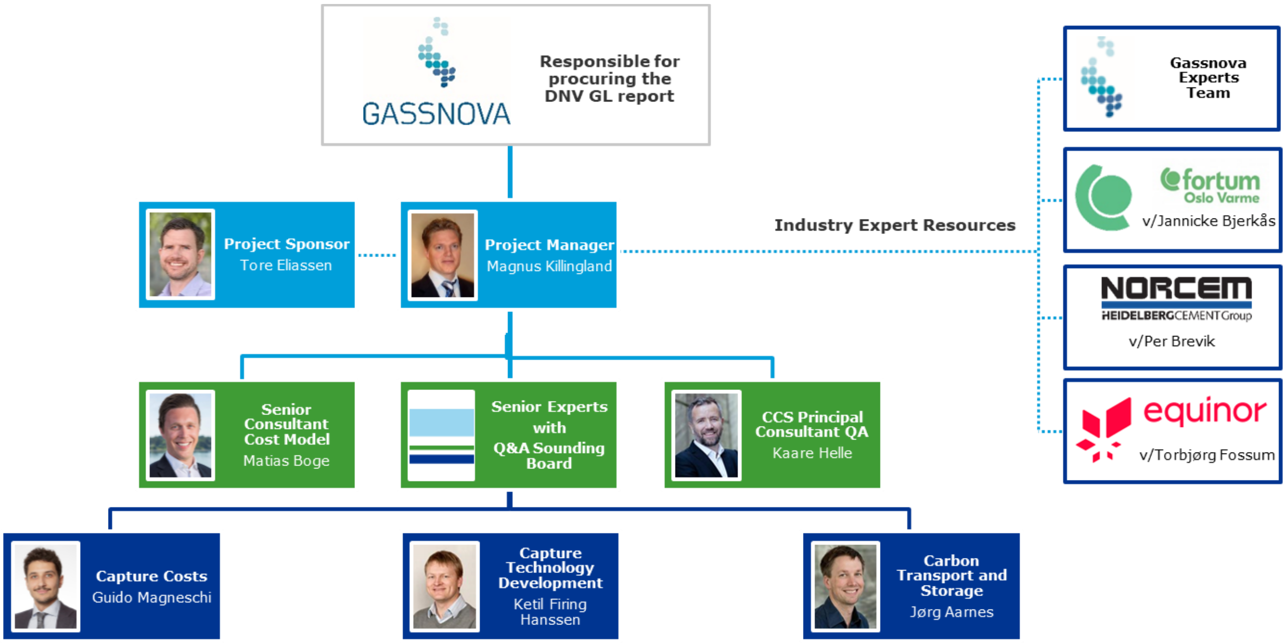


Figure 27 – CCS Cost Curve and Cost Reductions Project timeline

5.6.2 Involved parties and organization

The figure below shows the project organization and responsible project managers at each industry partner. The DNV GL project organization has reported to Aslak Viumdal and Tove Dahl Mustad at Gassnova.



About DNV GL

DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.