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NORDICCS CCS Roadmap

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Abstract

The Nordic CCS roadmap is developed in the NORDICCS project, a collaborative research project between leading CCS research institutions in the five Nordic countries. The roadmap will outline jointly developed Nordic strategies for widespread implementation of CCS in the Nordic countries in order to help Nordic industries meet a carbon constrained future with a high price on carbon emissions. It will identify pathways and milestones for large-scale Nordic implementation of CCS resulting in beneficial economies of scale that will increase the likelihood of implementation. Several novel cases will be presented that reveal future Nordic opportunities, including industrial CCS where emitters have large point sources of CO_2 localized in clusters, and natural gas sweetening with the potential for use of Enhanced Oil Recovery (EOR) to defray the costs. Recommendations will be made for actions relating to joint political work in the Nordic region for improving the framework conditions for CCS.

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Keywords: CO_2 Capture; Storage; Nordic; CCS; Carbon Capture; Roadmap; Implementation

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1. Introduction

The Nordic countries have all made strong climate commitments and have set their ambitions high, on a carbon-neutral scenario in which GHG emissions must be reduced by 85% by 2050. Carbon credits will be used to offset the remaining 15%[1]. The recent International Energy Agency (IEA) report Nordic Energy Technology Perspectives, 2013 suggests that CCS must account for more than 25% of industry emission reductions, and CCS also has to be applied to some electricity generation in order to reach this goal[1].

There are interesting opportunities and synergies in the Nordic region that can make CCS collaboration very rewarding. Firstly, this includes combining the vast biomass resources of Sweden and Finland with the significant CO_2 storage capacities for CO_2 off the coasts of Norway and Denmark. Storing the CO_2 emitted from bioenergy and pulp and paper industries provides the possibility for carbon negative solutions (i.e. removing CO_2 from the atmosphere through storing biogenic emissions) from several large-scale point sources. Secondly, other large industrial point sources like the steel and cement industries in the Nordic region can utilize the safe off-shore storage sites. The Nordic countries are therefore in a strong position to take a leading role in testing, demonstrating and implementing a wide variety of CCS technology options. Norway has already implemented two offshore CO_2 storage projects at Statoil's Sleipner and Snøhvit fields where 1.7 M tons of CO_2 are stored annually[2].Thirdly, the offshore storage opportunities lend themselves to the possibility of diverting the $CO_2$from the storage site to nearby producing oil fields for Enhanced Oil Recovery (EOR) projects when needed. Enhanced gas recovery projects may also be an option in the future. The use of the CO_2 for EOR will greatly improve the economics of the CCS projects. Capture costs must also be reduced in order to achieve widespread implementation.

There are therefore numerous opportunities for taking advantage of economies of scale by developing integrated transport and storage infrastructure serving several Nordic point sources. In addition, the close proximity of the storage sites to large CO_2 emission sources on the European continent will allow a joint Nordic development to also be extended to Europe and potentially benefit economically from even larger economies of scale. The region can thereby be a forerunner in providing cost efficient CCS systems, enabling Nordic industries to make deep cuts in CO_2 emissions. Several CCS cases – including both industrial and power plant point sources will be evaluated.

2. Background

2.1 Global, European and Nordic CCS Targets

It is generally accepted that the world's CO_2 emissions must be reduced in order to avoid serious climate changes. The parties under United Nations Framework Convention on Climate Change (UNFCCC) has set a goal of limiting the world's temperature increase to 2 degrees by 2050[3], meaning the CO_2 emissions must be reduced by 50% as described in the IEA's 2050 Blue Map Scenario[4, 5]. In the recent IEA roadmap on CCS, the analysis suggest that for an economic scenario to meet the 2050 emission targets 14% of all CO_2 emission reductions will need to come from CCS[5, 6]. The analysis supporting the IEA Blue map scenario calculates that it will be 70% more expensive to achieve the emission reduction targets without CCS than with[7].

The recent IEA CCS roadmap states that the technology and emissions path we are currently on must be changed if we are to meet the climate goals of keeping the temperature increase to below 2 degrees by 2050[7]. If internationally coordinated action is not implemented by 2017 any new investments thereafter must be zero carbon, i.e. either renewables or fossil based with CCS. The achievement of zero carbon is probably not realistic, and there is only so much CO_2 that can be emitted to the atmosphere. There will therefore be a need to go carbon negative through bio-CCS on many projects in the future in order to provide an operating space for developing countries at the same time as meeting the agreed climate goals. This suggests that CCS will be part of the solution for a long time. Industrial emissions represent a significant share of CO_2 emissions and CCS is the only option for reducing

CO_2 emissions from many energy intensive industries such as steel, cement, chemicals and refining. It can also help reduce emissions from existing facilities that are already locked in to emission intensive technologies, and may as such also help preserve the value of fossil fuel resources[8]. The European Union has set a 20% reduction target for the greenhouse gas emissions compared to 1990. Of these CO_2 emissions the energy industries are responsible for 35% and industry 18%[9]. The EU is also committed to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 in the context of necessary reductions by developed countries as a group as described in the 2012 EU Energy Roadmap 2050[9].

All the five Nordic countries have strong economies, and ambitions for helping protect the worlds climate through their plans for CO_2 reductions and visions for environmentally friendly energy systems,.

Denmark: Denmark is progressive in its plans for reducing CO_2 emissions. Currently 80% of its energy originates from fossil resources and they are aiming for 100% renewable energy by 2050[10]. And Denmark is to contribute to the EU goal of 80-95% reduction of climate gases from 1990 to 2050. To reach this goal oil for heating and cooling is forbidden from 2030 and the heat supply should be 100% renewable by 2035. The consequence of this is according to the recent governmental climate plan that no more fossil power plants can be constructed without CCS as their lifetime is typically more than 30 years[10]. The governmental climate plan proposes using CCS in combination with Enhanced Oil Recovery (EOR). It proposes implementing CCS on three power plants starting in about 2020, and shipping the CO_2 to oil fields in the North-sea for EOR. It is estimated that 4.5 M tons of CO_2 could be stored by 2027. It will be able to stay at that level going forward to 2042 and then decline by 2050. The government will pay for the differential losses the oil companies will incur in capturing and storing the CO_2 which is estimated to 7.4 billion a Danish krones annually[10].

Norway: Norway is unique in that its power supply is predominantly from hydropower, at 97% of the total. The CO_2 emissions originate from the oil and gas production (29%), industry (25%) and transportation (30%)[11]. Norway has set a goal of becoming carbon neutral by 2050 [12]. In order to do so, the CO_2 emissions inside Norway's borders must be reduced by 12-14 M tonnes of CO_2 equivalents relative to the 1990 emissions by 2020 The Norwegian government has taken a strong position in the support of CCS by funding significant R&D activities. Statoil has implemented two of the world's four first industrial scale CO_2 storage projects, Sleipner and Snøhvit. About 1.8 M tonnes of CO_2 that would otherwise have been released to the atmosphere are captured and stored on the Norwegian continental shelf annually. The extra costs in connection with the compression and injection of carbon dioxide at Sleipner amounted to about USD 100 million due to the high costs of implementing technologies in the island mode. The incentives for starting the storage were quite clear however. The natural gas contained 4-9.5% $CO_{2,}$ and had to be cleaned before export, and Norway had introduced a CO_2 tax in 1991 which further incentivised the offshore storage project[2]. The Sleipner storage operation has proved to be an excellent example of safe CO_2 storage. The carbon dioxide is injected into the Utsira sand at approximately 1000 metres below the sea level. The overburden of Utsira at the injection site is around 700 metres thick with a primary seal (50–100 m thick) consisting of regionally persistent mudstone. All experience so far indicates that the injected CO_2 will remain stored in the geological formation for several thousands of years.

Sweden Hydropower is the main source of electricity production at 53% together with nuclear power that contributes 40%. The resulting low CO_2 emission level from electricity production is also supported by a wide-spread implementation of combined heat and power plants, predominantly using biofuels, where the heat from the power plant is captured for district heating. Hence Sweden is currently on a trajectory to meet its short-term climate goals, although not the 2050 goals.
The CO_2 emissions originate mainly from industries such as pulp and paper industries, cement, steel, refineries as well as transport. There is a focus on reducing fossil fuels in transport and increasing wind power parallel to overall focus on energy efficiency and a proposed 85% reduction in CO_2 equivalent emissions[13]. In one scenario CCS is assumed to take a major share of the reductions from the industry sector, but is not applied until about 2040[13].

Finland has most of its power production from fossil, bio & nuclear. It has extensive industrial-scale use of biomass. The goal is an 80 % reduction in GHG by 2050. The Finnish government adopted the foresight report on long term climate and energy policy in 2009. A target was set to reduce Finland's greenhouse gas emissions by at least 80% from the 1990 level by 2050. VTT started a strategic project "Low Carbon Finland 2050" to assess the role of new technologies in moving Finland to a new low carbon economy[14]. The analysis has defined different low carbon storylines "Tonni" and "Inno" which differ in the levels of radical technological breakthroughs and degree of urbanizaition etc. by 2050. In both scenarios carbon capture and storage contributes significantly towards the CO_2 reduction, approximately 15 % of the total reduction[1]. The main challenge for Finland is that no large-scale storage locations are in its near proximity. Bio CCS is a great option in Finland due to the significant pulp and paper industry and biomass based power generation. At the current time bio-CCS would not count under the Emission trading system (ETS). A prerequisite for Bio CCS to happen is to include CO_2 of bio-origin under the ETS.

Iceland has a primary energy supply which is based on 85% renewable energy from hydro and geothermal sources. Hot water and heat originates mainly from geothermal heating with an extensive district heating system. Close to 100 % of its electricity is generated from renewables, 75% of which is hydropower, the rest geothermal. In 2010 the total annual CO_2 emission was 4.5 Mt, 41% from the energy sector (fossil fuel combustion 37% and geothermal energy 4%) and 40% from industrial processes. The metal industry, aluminium (1.2 Mt CO2 from 3 smelters) and ferroalloys (0.23 Mt CO2 from one smelter), was the source of 85% of the emission from industrial processes in the year 2010. [15]Iceland's goal is a 50-70% reduction in GHG by 2050 compared to 1990[16].The geology is highly tectonic and storage in Iceland is difficult, although mineral storage of CO2 in basaltic rocks is a potential option investigated in the Carbfix project. Carbonate minerals provide a long-lasting and environmentally benign carbon storage host. The main disadvantage of this method is that it can take a long time, years to thousands of years[17].

2.2 The role of CCS in Reducing Nordic CO_2 Emissions

Seen as one region, the Nordic countries have ambitions of a Carbon-Neutral Scenario (CNS) in which GHG emissions must be reduced by 85% by 2050 compared to 1990 numbers, and carbon credits will be used to offset the remaining 15% as reported in the IEA report Nordic Energy Technology Perspectives (NETP)[1].

Because of the reliance on renewables, the Nordic electicity generation is characterized by relatively low CO_2 emissions of approximately 100 g CO_2 per kWh. This is considerably lower than the global average of around 550 g/kWh and the EU avaerage of 430 g/kWh[1]. In the NETP 4 Degree Scenario (DS) emissions from electicity generation decreases significantly to 10% of the 2010 level by 2050 due to an increased share of renewables in the energy mix from 60% in 2010 to about 80% in 2050. In the 2 DS even more to almost negative due to a switch to wind power, biomass, nuclear fossil-fuel swithcing and CCS[1].

In the NETP analysis CCS becomes the most important technology after 2030 for reduction of CO_2 emissions from industry[1]. The targets for CO_2 removal by CCS for the different scenarios is summarized in Table 1. About 8 Mt CO_2 are captured with CCS annually in the power sector from biomass fired power plants in Finland and Sweden, while CCS must account for more than 25% of industry emission reductions with a total of 12Mt captured [1]. In the 2DS and CNS between 20-30% of the reduction in industrial CO_2 is achieved by using CCS in the iron and steel, pulp and paper, chemicals and cement sectors by 2050. About 7 Mt CO_2 is captured by Nordic Industry by 2050, in the CNS the captured volumes are 6 Mt CO_2, Table 1. The VTT scenarios Tonni and Inno applied to the Nordic energy mix represents a more optimistic view on CCS compared to the NETP scenarios, Table 1. The difference is largely due to a much higher projected contribution from Bio CCS which represents a large part of the CCS projects as shown in Figure 1.

Table 1: Targets for Application of CCS to meet the 2050 Climate goals for the Nordic Countries
Sources: Nordic Energy Technology Perspectives, VTT Green Energy, "Lavutslippsutvalget"

Country	CCS Target (Mt)			Source
	Industry	Power	Total	
Nordic ETP	12	8	20	International Energy Agency (2013), Nordic Energy Technology Perspectives, OECD/IEA
Nordic ETP 2 DS	**7**	**8**	**15**	International Energy Agency (2013), Nordic Energy Technology Perspectives, OECD/IEA
Nordic EPT CNS	6	8	14	International Energy Agency (2013), Nordic Energy Technology Perspectives, OECD/IEA
Toni	9	25	34	VTT Green Energy, 2013; Bio CS in pulp &paper
Inno	10	21	31	VTT Green Energy, 2013; Bio CCS in pulp & paper
Norway	3	19	22	Lavutslippsutvalget, 2006
Finland	14	4	18	VTT Green Energy, 2013; Includes Bio CCS in pulp and paper industry

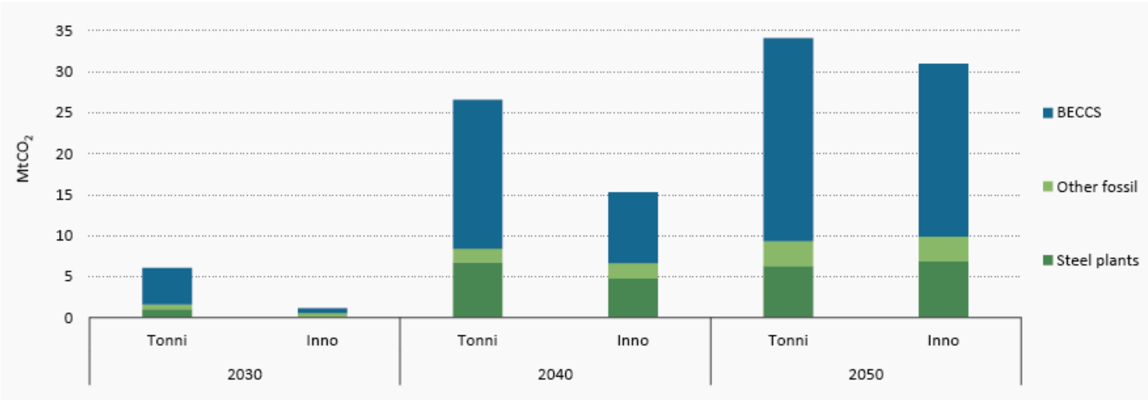

Figure 1: Targets for CO_2 removal by CCS by 2030, 2040 and 2050 for theTonni and Inno scenarios developed by VTT.
Source: *International Energy Agency (2013), Nordic Energy Technology Perspectives, OECD/IEA, Paris[1]*

2.3 Unique Opportunities through Collaboration on Nordic CCS Projects

Opportunities in Economy of Scale: There are potentially great benefits to gain from Nordic Collaboration on CCS. There are large point sources of CO_2 in Sweden and Finland, as shown in Figure 2, and vast storage capacities off the coasts of Norway and Denmark. The lack of storage capacity in Finland and Sweden means transport to Norway and Denmark for storage is a good solution. This would also result in great benefits of "economy of scale" as joint hubs and storage sites could be developed reducing the cost per ton of CO_2 stored.

Opportunity for Bio-CCS: The US projects are land based so less complicated to operate than offshore EOR projects. However,***CCS:*** The Nordic countries are unique in that a large amount of the CO_2 emissions point sources are of biogenic origin, as can be seen from the distribution of stationary emission sources by origin of source in Figure 3. That is particularly true for Sweden and Finland, Figure 3. The point emission sources for which CCS could potentially be applicable are more than 50% biogenic in Finland and nearly 40% of biogenic origin in Sweden. In Denmark, Norway and Iceland the point sources are almost solely fossil. Since CCS will be applied to industrial point source, there is great opportunity for applying CCS in bio-industry and bioenergy resulting in carbon negative projects. This is necessary in order to meet the 2050 goals[7] as there are already CO_2 emissions locked in by existing industries that cannot reduce their emissions. Hence the maximum allowable level to meet the 2 degree goal is exceeded.

Opportunity to Reduce Cost of CCS by utilizing CO_2 for Enhanced Oil Recovery (EOR): A major obstacle against widespread implementation of CCS projects is the high cost and low incentives. However CCS has been demonstrated to be profitable in commercial scale applications for nearly 30 years in the US due to the use of CO_2 for enhanced oil recovery. The bulk of the global application of CO_2-EOR comes from the Permian Basin of West Texas in the United States, which accounts for two-thirds of the world's oil production from CO_2-EOR projects[18]. In 2010, 56 M tonnes of CO_2 were injected into oil wells in the US to enhance oil recovery. The largest single source of anthropogenic CO_2 used for EOR is the capture of four million metric tons per year (230 MMcfd) of CO_2 from the Shute Creek gas processing plant at the La Barge field in western Wyoming[18]. This is followed by the capture of about three million metric tons per year(150 MMcfd) of CO_2 from the Northern Great Plains Gasification plant in Beulah, North Dakota and its transport, via a 320 kilometer (km) (200 mile) cross-border CO_2 pipeline, to two EOR projects(Weyburn and Middale) in Saskatchewan, Canada. At the Weyburn EOR project in Canada which stores approximately 1 MT/yr of CO_2 since 2000 and has injected 18 M Tons as of July 2010. The project costs US$ 80 M and it has extended the life of the Weyburn field by 25 years. Current cost is $20/Ton CO_2 [10]. Boundary Dam, the world's first coal based power plant with CCS is about to be opened in Canada in 2014. Here CCS will be economical due to the use of the CO_2 for EOR.

One study suggests that EOR storage is a prerequisite for future US CCS projects [12]. The US projects are land based so less complicated to operate than offshore EOR projects. However, the extensive offshore storage capabilities off the coasts of Denmark and Norway in in close proximity to oil and gas fields lends a unique opportunity for the reduction of costs of CCS by the use of the CO_2 in EOR also in the Nordic countries. In 2009 Maersk Oil planned to use CO_2 from a Finnish power plant and ship it to the North Sea for injection into a depleted oil or gas field for EOR/EGR purpose. However, this project was abandoned in 2011 and Maersk consider not enough captured CO_2 the main problem[19] . The lack of a constant supply of CO_2 has also been mentioned as one reason EOR projects cannot be performed readily on the Norwegian continental shelf. Another reason for difficulty in starting EOR projects at producing oil-fields is the loss in production time due to shut down of the platform for retrofitting EOR capabilities. The stage 1 separator must be retrofitted to withstand a well stream rich in water and CO_2. Hence it is important to consider EOR now for the new fields under development.

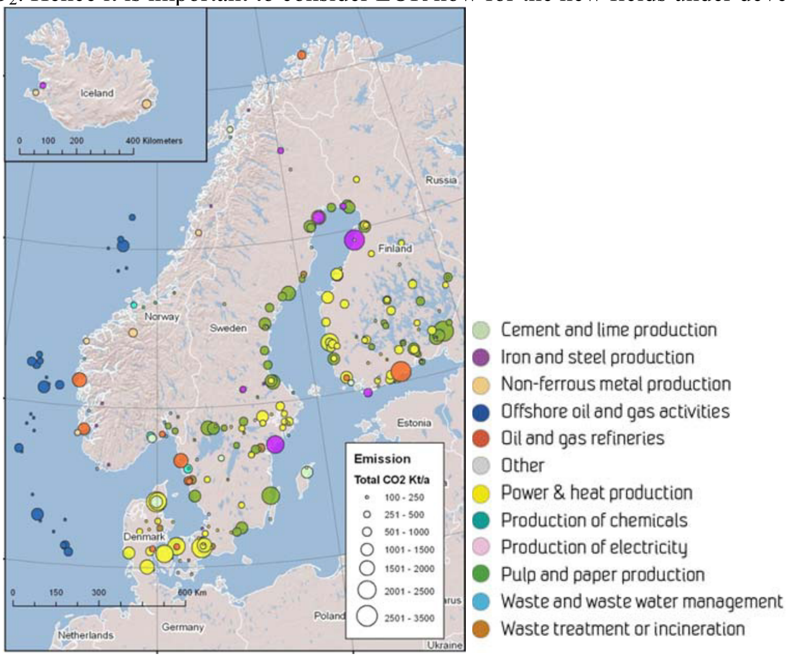

Figure 2: Industrial stationary point sources of CO_2 (>100 000 tonnes emitted/year)

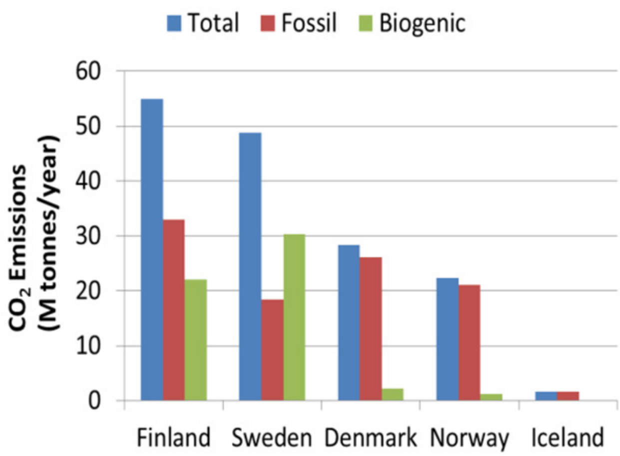

Figure 3: CO_2 emissions from industrial stationary sources (>100 000 tons/year)

In the NORDICCS project the focus is on increasing the likelyhood of implementation of CCS by analyzing the most cost-effective ways of performing CCS. That includes focusing on economy of scale, large size projects that would reduce the cost per ton CO_2 stored, projects that have the potential of later benefitting from EOR to reduce cost. CCS is also investigated for industries that have no other option for removing CO_2 other than CCS as CO_2 is a product of the manufacturing process. This is the case for both the Cement and Steel industries. Further, a main focus in the Nordic CCS collaboration is to promote implementation of BioCCS projects that have the possibility to go carbon negative. Based on these prerequisites, economical analysis was performed on 10 cases that were chosen as likely to become the most viable Nordic solutions for CCS.

3.1 Methodology Used for the Economic Analysis of CCS Case Studies

The economic analysis is based on a cost level of 2012 in the Euro Currency. Escalation is CPI in Eurostat. Rate of return is 8% and lifetime of the project is 25 years.

Capture Plant: In the calculation of capital expense (CAPEX) for capture plants it was assumed that the plant is N^{th} of a kind (NOAK). The first plant will be more expensive. A generic cost level is assumed, i.e. Rotterdam. The cost estimation assumes a brown site, i.e. an existing industrial area and an extension of the existing plant, no new operating organization included and using existing office and welfare buildings. It further assumes using existing infrastructure, power, steam, cooling water, process water, demineralised water etc. No purchase cost for land and no piling, No additional cost for offices, cantina and other secondary buildings. No extra pre-treating of the flue gas. CO_2 was delivered at 70 bar, 20 degree C and the capture technology is based on Tel-Tek's Amine based CO_2 capture process[20]. Flue gases are brought to the capture plant. All utilities are brought to the capture plant. Owner's costs are not included, and all costs are in 2012 Euro. Detailed factor estimate as used in CO_2 Capture Project (CCP) (CCP1-2006 & CCP2-2009). The estimates shall include first fill of chemicals. Cooling water temperature: 8 degree C + 15 degree C. The capture plant is at the peak value of CO_2/h. (not average). All operational cost (OPEX)are presented as 8760 hours operating time per year. Cost estimates were based on flow diagrams and equipment list. The equipment list included information of typical size, pressure, temperature and materials. The equipment cost shall either be budget quotes or estimated with a common database (Aspen in plant cost estimator). Costly equipment such as compressors, air separation units and power turbines shall use the same basis.

In the calculation of the costs of gas sweetening (CO_2 capture from natural gas), a high pressure MEA process was assumed. However a MDEA process is most likely to be applied for gas sweeeting. This process requires less steam and energy and has the potential of becoming even less expensive. The costs presented here for gas sweetening will be analyzed in more accuracy over the next year, and final numbers will be presented that are

Table 2: Variable Cost Factors Capture Plant

Variable cost	Unit	Unit cost (EUR)
Electric power	kWh	0,1
Steam (low pressure)	Tonne	15
Natural gas	Sm^3	0,3
Town water	m^3	0,015
Cooling water	m^3	0,0015
MEA (85%)	kg	1,8
NA2CO3	kg	0,6
Active coal	kg	5,5
Corrosion inhibitor	kg	1,9
Destruction of used MEA	kg	0,25

Table 3: Generic Price list for common utilities:

Fixed cost	Unit	Unit cost (EUR)
Operator	hour	50
Administrator	hour	60
Maintenace	% of CAPEX	4 %

expected to show even lower costs for the gas sweetening process. It must be noted that the additional benefit of utilizing the CO_2 for EOR as well as the benefit gained from increased heating value of the natural gas by reducing the amount of CO_2. ***Location factors:*** Location factor shall be divided in: Extra cost (CAPEX), reduced efficiency (CAPEX) and special conditions (OPEX) – the details are shown in Table 4.

Table 4: Location Factors

Extra cost (CAPEX)	Reduced efficiency (CAPEX)
Travel and living cost of “imported” constructors	Ex-situation under construction (work permit)
Extra transportation cost	Waiting time
Extra for ex-proof installations	Rain/snow
Long-time renting of special equipment (cranes)	Cold weather
Special systems for type of industry	

Transport and storage*:** The condition of CO_2 shall when passing the “borders” have a pressure of 70 bar, temperature at 0 to 30 degree C at sea level. The cost estimation must be done with the same tool (simple) in order to compare the results. The method should be verified with a more sophisticated system. ***Sensitivity: The estimates are analyzed to find the main cost drivers; Energy cost, Investment cost, Rate of return, Operating hours/year, Chemicals.

4.0 Results

The cost for capturing and storing CO_2 for selected Nordic Cases are shown in Figure 4. The costs are broken down in Capture , Transport and Storage costs. The capture costs assume using the Tel-Tek MEA process. Many of the cases that come out the most economically promising are in the Skagerak industry cluster. The Skagerak industry cluster is a collection of large industrial point sources of CO_2 are located in close proximity as illustrated in Figure 4. An added benefit is that the sources are also close to a potential storage site in the Gassum formation in Skagerrak or by easy transportation by ship to the well-characterized Utsira formation off the coast of Norway. The potentially large scale of the project if several of these sources are captured and stored could make it possible to utilize the CO_2 for EOR projects in nearby oil fields. The industries analyzed are Norcem Cement plant, Norway, Esso Refinery, Norway, Preemraff Refinery, Sweden, Chemical Plant, Sweden, Portland Cement, Denmark, Nordjyllands verket, Denmark, Kårstø, Norway. The proposed hub is at Hirtshals, Denmark or Kårstø

Norway, location will be chosen closest to the first capture site with transport by ship to the storage respectively at the Gassum formation in Skagerak or to Utsira in Norway.Both Portland cement as well as Norcem cement in Brevik, Norway come out in the lower cost range. The Norwegian government through Gassnova has awarded NORCEM a project for a CCS test facility at their Brevik plant.

The most economically viable case however is gas sweetening, i.e removal of CO_2 from natural gas before export to Europe. As can be shown from Figure 4, the capture costs are the lowest. And this cost is likely to be reduced further by estimating costs using the less energy demanding MDEA capture process. The cost calculations also shows significant redution in capture cost with increasing volume, Figure 5, indicating that economy of scale is important for volume captured up to 2-3 M tonnes/year. The capture cost for an n^{th} of a kind plant closes in on 40 euros/tonne when the volume of the site increases up to 3 Mtonnes/year. The production of relatively inexpensive CO_2 on a large and steady scale would allow for the potential implementation of large-scale EOR projects.

Previous EOR projects in Denmark and Norway have failed due to the lack of a large volume, steady supply of inexpensive CO_2. This has also been the achilles heal against expanding EOR in the US to a larger scale[18]. In order to"sweeten the deal" for CCS, there could be a good opportunity in natural gas sweetening, i.e in in removing and storing more of the CO_2 present in Norway's Natural Gas Currently Exported to Europe. The gas curently contains up to 2.5 % $CO_{2.}$ .More of this CO_2 could be removed from the natural gas relatively inexpensively and stored. Currently Norway is exporting about 100 B Sm3 annually, i.e. over 5 M tonnes of CO_2. It will be hard to modify existing infrastructure of pipelines to accommodate CCS both due to the high cost of construction in explosive areas as well as safety of supply. This case scenario was therefore calculated based upon a yet to be determined source of CO_2 from any new oil and gas field either at Utsira or in Northern Norway or the Arctic.

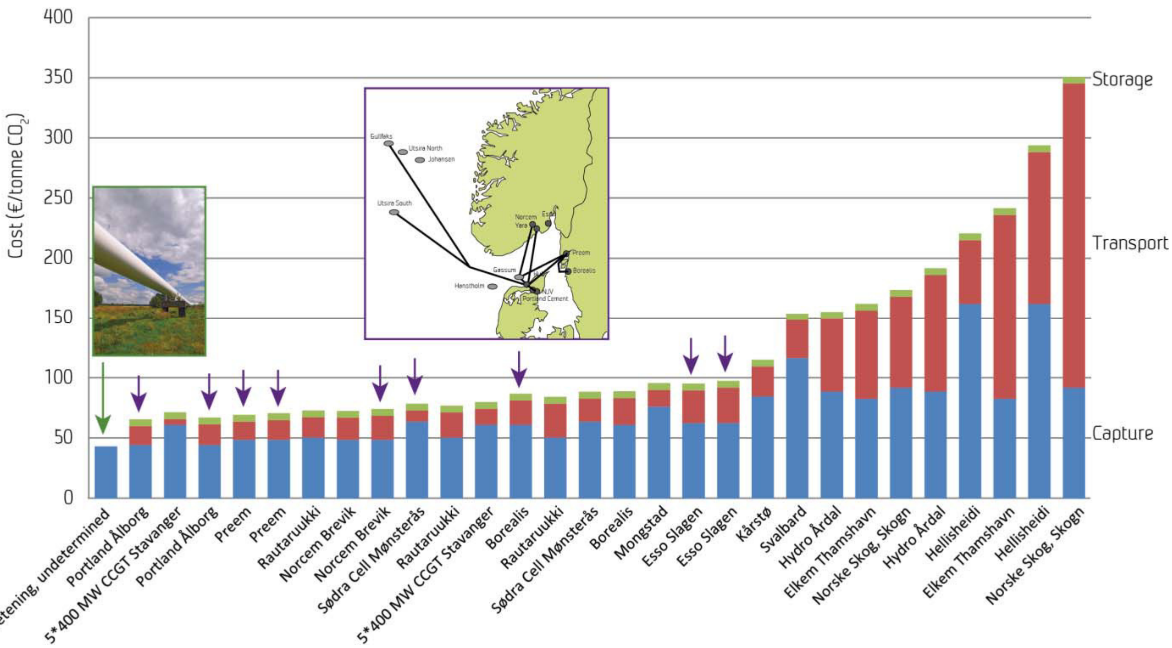

Figure 4: Cost Estimates for Nordic CCS Cases

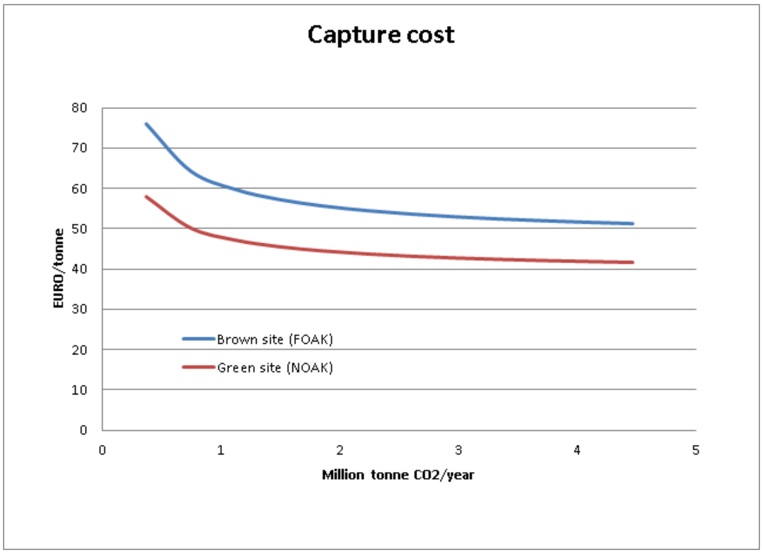

Figure 5: Economy of Scale for Natural Gas Sweetening Capture Costs

And it is particularly interesting in areas where the CO_2 concentration of the natural gas is high. In addtion to the cost benefits from selling the CO_2 for EOR there is additional benefit in that the natural gas will contain less CO_2 and therefore be more valuable per tonne as it is sold based on heating value. Potential economy of scale could be significant here and projects of CO_2 stored of about 2 M tonnes per year are not unrealistic. In addition the source and sink has the potential of being very close giving additional benefits of short transport distances and low costs.

The NORDICCS CCS roadmap is shown in Figure 6. "Scenario 1" illustrates current status where Statoil is capturing and storing 1.7 M tonnes of CO_2 at the Sleipner and Snøhvit oil and gas fields in the North sea. The Sleipner field will come to and end of its life towards 2030. However other nearby fields are coming online and CO_2 will be coming from the Gudrun field that is under construction and will come online by 2017.

In Scenario 2 the Norwegian government will likely implement the Carbon capture and storage project from one plant in Norway by 2020. A previuos candidate was a full scale project at the Mongstad power plant where another 0.5- 1 Mtonnes of CO_2 were proposed captured and stored but this project has been cancelled and another project may be put in place instead.

Scenario 3 indicates a natural next step that is to implement new gas sweetening projects that could reasonably come online as we approach 2020 and their potential for steady long-term supply of large volumes of CO_2 would make them good candidates utilizing the CO_2 for EOR to help defray costs. Three projects are assumed by 2050 each capturing about 2 Mtonnes of CO_2. These projects could provide the necessary sources for CO_2 needed for EOR and could help kick-start CCS in the Nordic Region by paying for the CO_2 storage and hubs in order to reduce costs for CCS from industrial sources. The potential for applying EOR would reduce the cost of CCS meaning that Scenario 3 has a lower threshold for implementation than Scenario 4, which is industrial CCS.

In Scenario 4 CCS is applied to the larger scale CCS industrial project in the Cement and Steel industry which have no other means of reducing CO_2 emissions than CCS as the CO_2 is a product of the production of steel and cement. The cost calculations were performed using an amine process. However, as the ULCOS project has shown solid adsorbents such as activated carbons and zeolites could be used in a PSA process. According to Air Liquide a capture cost of 25€ is possible per ton of CO2 for large scale steel plants. The costs for cement processes will be slightly higher due to the CO2 concentration of 22% as opposed to 25% for the steel plant with some overpressure. Implementation of BioCCS will be necessary to go carbon negative on some projects.

However in order to implement Scenario 4, changes are needed to the Framework conditions for CCS in the Nordic Countries. The current European carbon market is not proving to be effective. The cost of carbon emission is too low, and Norway is not in a position to influence it. It is too inexpensive to emit CO_2 in the EU to incentivize CCS. In order to implement Scenario 4 incentives such as CCS Certificates may need to be implemented. Here a minimum share of low-carbon energy is demanded from fossil fuel suppliers by either producing it or buying certificates. For example, inorder to sell one tonne of natural gas, a supplier would need to buy CCS Certificates offsetting the emission caused, which would be in the order of 2.3 tonnes of CO_2. The main advantage is that a specific binding target would be set for CCS deployment by policymakers, while the market sets the price for the certificates to fulfil the volume. Feed.-in-tarriffs can also be considered. Here long-term contracts are offered based on the cost of generation of each technology. They often involve a tarriff degression where the tarriff ramps down over time to stimulate innovation and technology improvements. A similar incentive "Contracts for Difference" is under legislation in the UK at the moment[16]. It gives incentives for investments in low- carbon electricity projects, tax credits, and will likely become law\ in 2013. Also the british government has legislated during 2013 to establish a Carbon Price Floor to secure a minimum price for emissions for companies included in the ETS. If the EU trading system included biogenic sources of CO_2, emissions from pulp production could be a target for CCS applications in Finland [13]. As a first step to facilitate bio-CCS, the EU carbon trading system should be altered to include biogenic sources of CO_2.

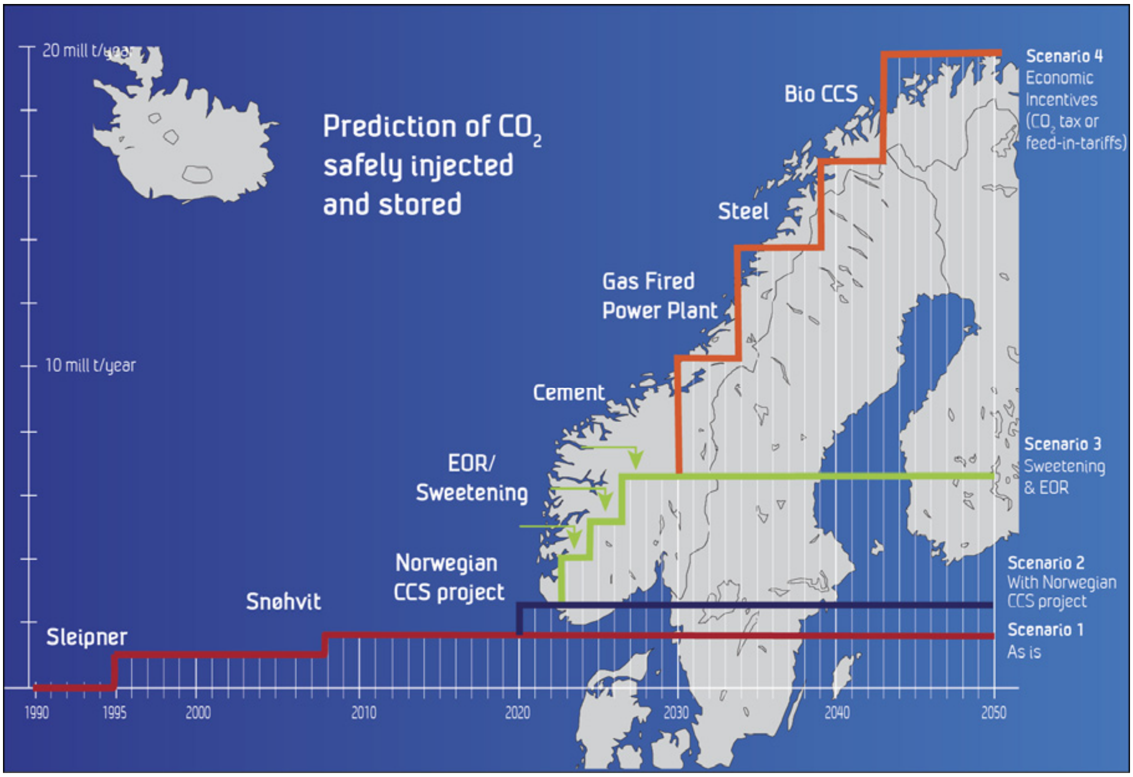

Figure 6: NORDICCS CCS Roadmap for Implementation of CCS towards 2050.

5. Conclusions

Our analysis of the Nordic energy supply suggests that a minimum of 20 M tonnes of CO_2 should be stored annually 2050 in order to meet the Nordic climate goals of carbon neutrality. The combination of enhanced oil recovery using CO_2 (CO_2-EOR) and permanent CO_2 storage in oil reservoirs has a critical near-term solution for creating economically viable CCS projects, facilitating early CCS infrastructure – and kick-starting deployment of CCS. It represents a win-win situation as it combines CO_2 capture from industries that need CCS with the use of CO_2 injection to increase oil production, thus financing a significant element of the project.

The economic analysis performed in the project suggests that gas sweetening projects should have the initial focus, as they have the potential of being less costly, and therefore have a lower threshold of implementation than industrial or power CCS projects. Natural gas sweetening can potentially be larger projects that provide the steady supply of CO_2 that can kick start an EOR project which in turn will create a market for CO_2 that can reduce the cost of CCS for land-based industry.

The analysis shows that CCS projects for the cement and steel industries are relatively economically viable. New CCS projects should be focused in these industries that have no other means of eliminating CO_2. Another focus area should be a demo project involving biomass capturing CO_2 from a pulp or paper plant in Sweden or Finland or from a bio energy project in order to prove the potential of going carbon negative. By joint efforts the Nordic Countries are more likely to succeed in developing the framework necessary for implementing CCS. It will put the region in a stronger position to influence the EU on key factors that will improve the likelihood of implementation, such as the European Carbon Market, where the cost of carbon emission is too low to spur implementation of CCS right now. Bio emissions may need to count to go carbon negative. Risk Distribution is necessary to reduce the risk for industrial actors. The government may need to share the liability for what could happen to the storage sites hundreds of years down the line. CCS Certificates may be implemented for fossil fuel supplies which demand a minimum share of low-carbon energy in their energy supply or produce certificates equivalents to this. The main advantage is that a specific binding target would be set for CCS deployment by policymakers, while the market sets the price for the certificates to fulfil the volume. Feed-in-tariffs may be necessary to initiate much needed CCS projects for the Cement and Steel industry.

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