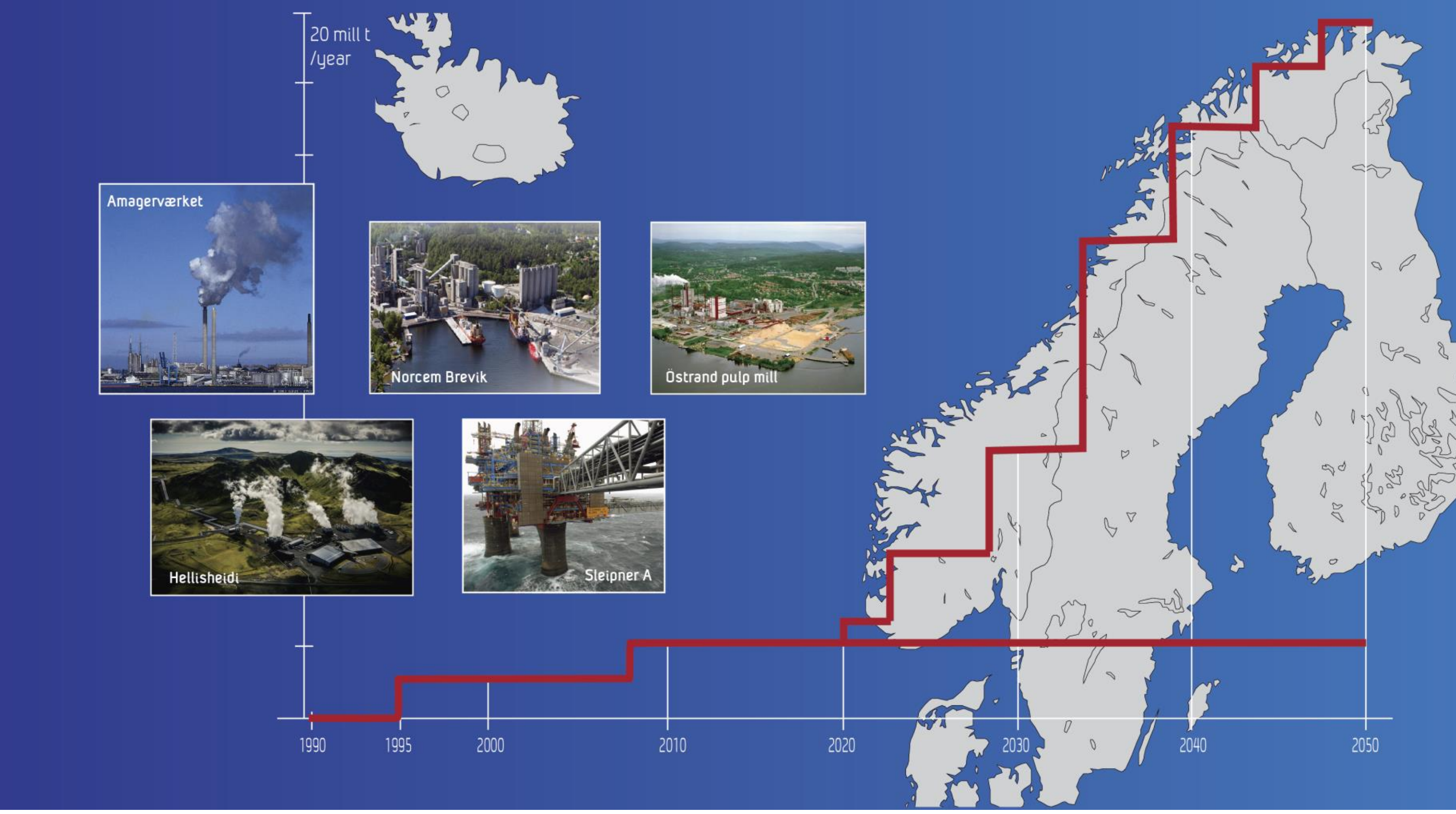


# CCS knowledge gaps

## Recommendations for R &D and innovation

## in the Nordic countries

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**NORDICCS Technical Report D3.15.1506**

**Core deliverable: D15**

October 2015

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Top-level Research Initiative

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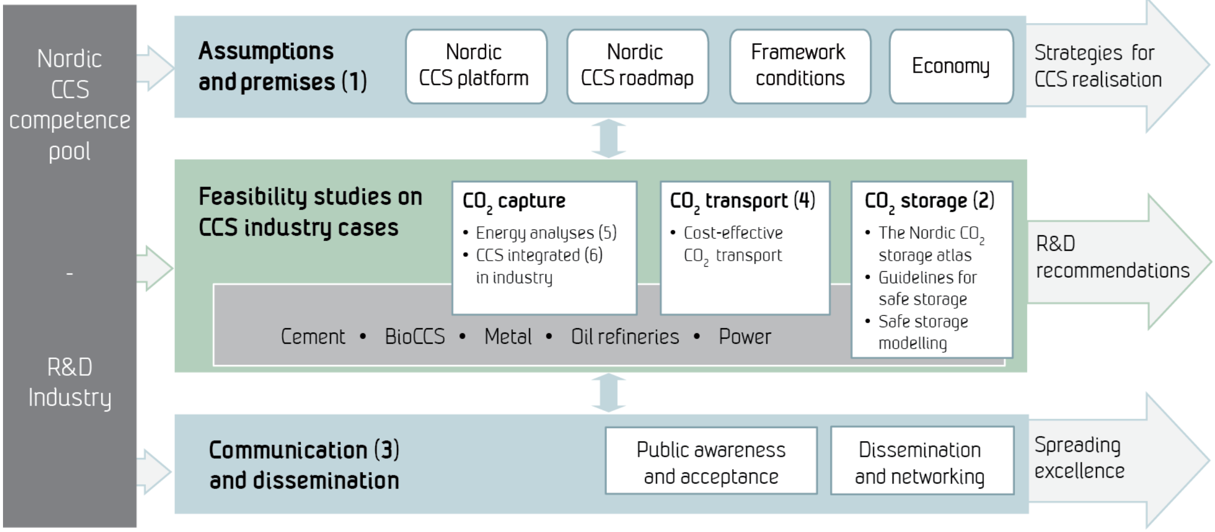


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# Summary

This report assesses the CCS knowledge gaps and possibilities for innovation for the Nordic region.

There are several main areas which are important in a Nordic CCS setting. The region has several industry sources located close to sea and also large biomass based industries and resource base. In addition, has the region several potential offshore storage sites, and also a well establish ship transport culture and offshore pipeline network.

More cost effective capture technologies suited for each individual plant/site needs to be provided. Post-combustion technologies seem the best short term solution for existing plants and further R&D and studies are required to qualify low energy absorbents/adsorbents, other novel gas separation technologies and cryogenic technologies. . Efficient capture of biogenic $CO_2$ emissions can provide carbon negative solutions and should be developed.

Even though pipeline and ship transport of $CO_2$ are already established today, although in small scale, development of a functional $CO_2$ network and infrastructure as part of the CCS chain is a challenge in the Nordic countries. Development of large scale transport solutions will probably include mixed transport modes. Special technologies are needed for offshore unloading of $CO_2$. Injection of $CO_2$ via subsea installations into geological storage will require development work, testing and qualification. Impurities in the $CO_2$ are a challenge with regard to safe and optimal choice of materials. Dynamic and transient situations should be modelled to find safe designs and process control solutions. Better thermodynamic data for impure $CO_2$ should also be obtained.

Long term, safe, reliable and publicly acceptable offshore $CO_2$ storage is crucial for Nordic CCS deployment. For many potential storage sites more data are needed to understand storage mechanisms, dynamics of $CO_2$ in the reservoir as well as to determine suitable monitoring techniques and mitigation measures in the event of $CO_2$ leakage. More injection pilots should be established to increase knowledge and provide experience in different reservoir types. At the same time, this will build public confidence to offshore $CO_2$ storage.  $CO_2$ driven EOR is still an opportunity in the North Sea which potentially could change the economics of CCS in a positive direction. $CO_2$-EOR should therefore be studied further in a Nordic context.

In order to close these knowledge gaps a closer cooperation between academia/ research institutes and the various industries and power producers is required. Finding adequate incentives to promote such cooperation projects is therefore essential.

**Keywords** CCS knowledge gaps, R&D activities, future activities

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**Date** October 2015

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***About NORDICCS***

*Nordic CCS Competence Centre, NORDICCS, is a networking platform for increased CCS deployment in the Nordic countries. NORDICCS has 10 research partners and six industry partners, is led by SINTEF Energy Research, and is supported by Nordic Innovation through the Top-level Research Initiative.*



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# Contents

## Introduction

This report is a delivery from WP 3 aimed at providing R&D recommendations and opportunities for innovation within CCS in a Nordic perspective. In April 2015 a workshop was held in Copenhagen involving participants representing all work packages in the NORDICCS project. The topic of the workshop was; CCS knowledge gaps and lessons learned during the NORDICCS project.

Carbon capture and storage (CCS) is relatively well understood technically and an extensive and solid competence base exists within Nordic academia, institutes and many industries. Norway has pioneered offshore $CO_2$ storage in geological formations through the Sleipner and Snøhvit projects. Hence, unique and extensive experience exists underpinning further deployment of CCS in the Nordic countries.

However, there are barriers to overcome if the ambitious 2030/2050 goals for $CO_2$ reductions shall be met. CCS will be a significant part of the solution. On the capture side high operating costs due to energy needs is still a major challenge and must be addressed. Innovative designs and new technologies to reduce investment and capital expenditure is another challenge. $CO_2$ capture from many types of industries is required and integration of the capture and core plant is an issue. In some cases such as the aluminum industry significant modifications to existing technology will be needed to facilitate carbon capture due to low $CO_2$ concentration (ca. 1 vol-%) in the flue gas. Utilization of the large biomass potential in Norway, Sweden and Finland represents an exciting area to explore also in the CCS context, in particular as this can provide carbon neutral or even carbon negative strategies.

$CO_2$ transport has routinely been employed in industrial operations for decades both in pipelines and ship carriers, although in a small scale (around 1000 tonnes/cargo). In the Nordic countries many medium sized $CO_2$ point sources exist and a cluster concept has been proposed with export hubs for transport to the storage site. Due to the long distances to adequate underground storage options for many industrial sources, ship transport seems to provide the lowest transport cost. This opens for innovative concept development including transient storage and offshore unloading and injection into the reservoirs.

$CO_2$ storage in the Nordic area will predominantly be into offshore subsea reservoirs or aquifers. There is a need for investigating a number of relevant storage structures to secure safe and optimal injection in order to reduce costs and possible future liabilities. Development of reliable monitoring techniques to detect possible leakages and implement mitigation measures are other challenging topics. Developing offshore EOR concepts using $CO_2$, is an interesting option for North Sea oil production, with the potential to kick-start CCS projects. Additional knowledge to increase understanding of EOR-mechanisms is required. There is also a need to develop cost effective, compact handling of $CO_2$ in the offshore separation processes to reduce the cost of $CO_2$-EOR:.

Apart from CCS cost there are other, non-technical, barriers. These barriers include development of business models for the CCS chain, issues relating to securing public and political understanding and acceptance as well as legal issues. .  A new legal framework is needed to provide a safe environment for implementing widespread, large-scale CCS in the Nordic countries.

## Technical knowledge gaps

### Capture

When examining the implementation of CCS in existing industry plants in the Nordic countries, post-combustion technologies seem to offer the most relevant short term option. The flue-gases from the different industry plants such as refineries, cement plants, petrochemical plants, pulp and paper plants, and steel production have different characteristics which have to be handled by the $CO_2$ capture plant. This holds also for the coal and natural gas fired power plants.

Post-combustion capture technologies are essentially end-of-pipe solutions and implementation can occur with limited modifications to the core process plant. However, finding available space and location for flue-gas ducting and the capture plant itself can be challenging within existing, normally congested industry sites. Procedures are required to allow normal and safe operation of the core plant during capture plant construction and to secure as short as possible shut down period for integration of the two plants. The capture plant requires large energy input, typically steam and/or electricity, and other utilities such as cooling water etc. To find an alternative energy supply by using low-grade waste energy in the core plant, or to use biomass or other renewable sources requires solutions specific for each industry site. Pretreating the flue-gas from the core plant may be required before entering the capture plant to reduce contaminants such as $NO_x$, $SO_x$ and dust that are harmful to the post-combustion technologies. Developing new technologies reducing the need for pretreatment, and having a low energy requirement, is an R&D challenge. Cryogenic concepts may represent interesting options particularly for applications to flue-gases with high (>15 vol-%) $CO_2$ concentrations. Other post-combustion technologies based on innovative absorption or adsorption materials and, for example, membrane separation processes need to be further evaluated and developed to find the real potential improvement to overall energy requirement as well as plant investment cost.

To improve our scientific, fundamental understanding of the post combustion capture technologies, thermodynamics and kinetics for relevant systems, including mixed amines systems, should be investigated further. The effect of typical flue-gas contaminants on process performance should be better understood. This will benefit the modelling capacities and reduce technical design risks.

The $CO_2$ concentration in the flue gas can influence the choice of capture technology and the need for core process modifications. In aluminum production the $CO_2$ concentration in the process flue-gas is approximately 1 vol-% resulting in the need to handle large gas volumes in the capture plant relative to the amount of $CO_2$ to be captured. Inside each production cell, however, the concentration is more than 99 % when no air is added. It is therefore an interesting question as to whether the process can be modified technically to enable direct capture of such a highly concentrated $CO_2$ stream.

Certain technologies, for example cryogenic processes, may benefit from high (>15 vol-%) $CO_2$ concentrations in flue-gases such as those from cement plants. As a consequence energy and investment needs may be reduced.

Pre- and oxy-combustion technologies will require changes in the core plant if applied to plants already in operation and is therefore normally a more demanding and long term solution for CCS implementation. For instance, in cement production, oxyfuel technologies can be anticipated to provide a simpler route to $CO_2$ capture and should be further researched. If completely new core technologies need to be developed they must be proven in large scale operation, which is both resource and time consuming.

In oxy-combustion technologies, an air separation unit (ASU) is needed. ASUs are standard process units already available today, but research is ongoing to reduce the energy consumption. This should be continued. Another challenge is the need to purify the $CO_2$ stream after oxy-combustion. The purification need depends on the origin of the $CO_2$ (core plant) and the impurity limitations imposed by the rest of the CCS chain (transport, storage, EOR).

Pre-combustion technologies normally imply use of hydrogen for energy production in furnaces/boilers and turbines. Ample technology adjustments will be required for these process units to be able to handle this fuel within the environmental constraints for each particular plant. $NO_x$-emissions for example, represent a real challenge in this respect.

Generally, there are scale-up and operational as well as process regulation issues that need to be looked into and resolved for each industry plant when implementing CCS technologies.

Within the Norwegian natural gas production system an interesting innovative option exists in enhanced gas sweetening (which is done at high pressure) to capture more $CO_2$ from the export gas and then reinject $CO_2$ for underground storage. This is a relatively low cost $CO_2$ capture option and has an economic upside due to increased capacity in the gas exporting pipelines.

## Transport

There are two transportation modes considered for large-scale implementation of CCS; pipelines and ships. Both transport modes are relevant. A combination may represent the most cost effective transport solution when deploying CCS in the Nordic countries. Export and import $CO_2$ hubs may be part of the transport infrastructure as nodes in the $CO_2$ chain. The initial development of the transport network and further ramp-up to full design capacity need special attention and innovative concepts to find cost effective solutions.

Material and safety issues are two areas with knowledge gaps relevant for both transport modes. As commercial CCS will imply $CO_2$ with some contaminants, depending on industrial source and capture technology, this has to be taken into consideration when selecting materials for construction of both pipelines and tanks. This will influence both the cost of transport as well as safety aspects of operation and injection well specifications for storage.

There is a lack of accurate data on thermodynamic properties of $CO_2$ mixtures including the effect on corrosion in pipelines, tanks and injection wells. Also, more knowledge is needed as to under what conditions (pressure, temperature, and degree of impurities) hydrates can form. There is a need for improved tools for simulating the behavior of $CO_2$ with impurities.

## Pipeline transport

Onshore pipeline transport of $CO_2$ has been practiced on a large scale in the U.S./Canada for decades, where $CO_2$ is transported to Enhanced Oil Recovery (EOR) injection sites. Offshore $CO_2$ pipeline transport (150 km, 700 ktonnes/year) has been in large-scale operation between the onshore gas treatment plant and the Norwegian Snøhvit field for geological storage since $CO_2$ injection started there in 2008. Transport conditions vary depending on the mode. High pressure is used in pipelines such as the Weyburn US/Canada pipeline with a delivery pressure of 150 Bar. However, when implementing CCS in the Nordic countries, transport conditions should be optimized for each individual transport route, depending on distance and volumes of $CO_2$.

Pipeline integrity control is one issue that requires careful consideration in the design of a $CO_2$ pipeline. $CO_2$ pipelines may be more susceptible to long running ductile fractures than hydrocarbon gas pipelines [4.]. The need to prevent such continuous fractures imposes either a minimum required toughness or a requirement for mechanical crack arrestors and is an area for further investigation. Filling and emptying of $CO_2$ pipelines must also be executed with care, since this may also cause low temperatures.

## Ship transport

Commercial ship transport of purified $CO_2$ has also been going on for decades, as part of the value chain for use in industrial and consumer markets. Typical cargoes are around 1000 tonnes of $CO_2$ at 15-18 bars and -22 to -28 ºC. In the CCS chains, cargo capacities about 20 times larger are required and represent a potential development opportunity and market for the shipping industry.

Intermediate storage requires energy and is expensive. Such storage tanks can be optimized for pressure, temperature and size to make the most cost effective solution for ship transport. The optimal pressure and temperature for ship transport and injection needs more investigation, especially if there are impurities in the $CO_2$ stream.

In the case of offshore unloading and injection of $CO_2$ from ships, reheating of $CO_2$ is an issue which has to be addressed. This may partly be done by heat exchange with sea water, and the rest by utilizing excess heat on the injection platform, if available, or more likely from the ship. More research and process studies are needed to investigate how heating of the $CO_2$ can be conducted in the most cost efficient way. Little attention has been given to how to take care of "cold energy" from the transport vessel when unloading $CO_2$. This may deserve further evaluation. All these questions should be addressed and evaluated.

Liquefied $CO_2$ (-50ºC, 7 bar) is the most obvious choice for ship transport, but even ships carrying compressed, gas phase $CO_2$ have been suggested. Transporting compressed $CO_2$ can be compared to transport of $CO_2$ in pipelines. Transport conditions will therefore be similar to that of pipelines, but with more flexibility and ease of inspection than pipelines. The temperature should be about 25°C and the pressure above 75 bar. The concept of compressed $CO_2$ on ships has been developed by ship companies, but remains untested and no international regulations exist for such transport of $CO_2$.

Ship transport of $CO_2$ probably means empty ships on return from the unloading site and back to the export terminal. Possibilities for carrying return cargo could present an opportunity for cost reduction in special cases. Conditions such as cargo capacity of the ships, time to clean the tanks, unloading and loading times etc. must be taken into account.

Attention should be given to special transient situations and interfaces, for example, during emergency shut-downs, normal start-up and shut-down situations, and disconnection of the unloading ship, which may cause problems on the platform, for the injection well or subsea installation. Additional equipment might be needed to secure safe pressure and temperature conditions in these situations, and better knowledge and transient modelling capabilities should be developed.

## Storage/ EOR

The Nordic $CO_2$ storage atlas [2.] shows a large potential for offshore geological storage of $CO_2$ in the Nordic region. The North Sea and Skagerrak area are particularly interesting having several attractive storage options with large storage capacities (>1 Gt). However, the estimated capacities are highly uncertain. Improved reinterpretations of existing seismic surveys and exploration well data, supplemented with data from new seismic studies and well bores are needed, in order to obtain better data for reservoir characterisation. This is especially the case outside the well-documented oil and gas exploration areas, for example, the Skagerrak area.

Injection well design, capacity and location have significant effects on storage cost. More investigations regarding optimal placement of injection wells in relation to production wells are required in order to find the ideal well patterns. Impurities in the $CO_2$ can also affect $CO_2$ injection and storage, and needs further research. There is a clear need for improved knowledge regarding how specific hydrocarbon fields may respond to impure $CO_2$. Pilot well injection tests are another important research area, where verification of the reservoir properties and improvement of reservoir models are relevant themes. This can reduce the $CO_2$ injection methodology and costs.

If ship transport with direct offshore injection is used, a consequence will be an intermittent supply of $CO_2$. The impact of this on the reservoir and consequence for $CO_2$-EOR or storage of $CO_2$ are themes to be investigated.

There is still a need for improved modelling tools for subsurface $CO_2$ storage and monitoring methods to understand storage mechanisms and detect possible leakages.

Using $CO_2$ for EOR is an interesting opportunity for certain North Sea oilfields which may help kick-start CCS. However, offshore $CO_2$-EOR is particularly challenging, implying relatively high costs while impacting ongoing oil production. Better understanding of EOR mechanisms on each particular oilfield and innovative solutions for modifications to topside gas separation and processing are needed when large volumes of $CO_2$ are introduced to the oil reservoir.

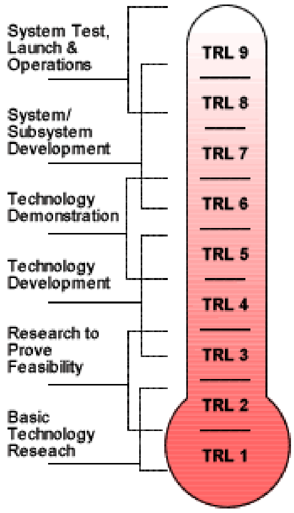
There is a need for both static and dynamic analysis of flow, temperatures, pressures and the resulting stresses, both in pipe and well design. Material requirements should be analysed on this background, covering the full piping system and the well itself.

## Technology Readiness Level

Technology readiness level (TRL) is described in a white paper from NASA 1995 [5.]. The description of TRL below is based on this paper. TRLs are a type of measurement system used to evaluate the maturity level of a technology. Each technology is evaluated against the parameters for each level and is then given a TRL rating based on the project's progress. There are nine technology readiness levels, where TRL 1 is the lowest level and TRL 9 is highest..

When a technology is at TRL 1, scientific research is in its beginning. TRL 2 occurs once the basic principles have been studied and practical applications can be applied to those initial findings. A TRL 2 technology is very speculative, as there is little to no experimental proof of concept.

When active research and design begin, a technology is elevated to TRL 3. Generally both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept model is constructed. Laboratory- and bench-scale processes correspond to levels 3, 4 and 5 on the TRL system.




Technology Readiness Level (TRL) [5.]

Once the proof-of-concept technology is ready, the technology advances to TRL 4. During TRL 4, multiple component pieces are tested with one another. TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is at TRL 4. Simulations should be run in environments that are as close to realistic as possible. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model.

TRL 7 technology requires that the working model or prototype has been demonstrated in a large scale. For carbon capture technologies, a pilot plant would correspond to TRL levels 6 and 7. TRL 8 technologies have been tested and are ready for implementation into an already existing technology or technology system. There are many descriptions for when a technology is at level 9. The report "Carbon Capture: A Technology Assessment" [6.] describes level 9 as "Once a technology has been demonstrated in full scale, and offered for sale by one or more vendors with standard commercial guarantees over some time, it can be called TRL 9".

Looking at the three main types of $CO_2$ capture technologies, ; (post combustion, pre combustion and oxyfuel combustion) the technologies are currently at quite different TRL levels. Many amine-based post combustion capture technologies are already at TRL 6-9 based on the fact that such plants are running and this technology has been available for several years. There are still optimizations and improvement to be done, but mainly this technology group is well understood and demonstrated. Pre-combustion has not been tested in full scale, and the TRL level is likely between 3 and 6.The technology is well understood, but there are still challenges regarding $H_2$ combustion and air separation that need research and further development for capture in large scale. Oxyfuel technologies are aspiring, but still not demonstrated in large scale. Therefore the we assess TRL levels to be around 2-5. There are many studies and ongoing work to reduce costs and improve the performance of the ASU (air separation unit) that is needed in oxyfuel processes.

Ship transport of food grade $CO_2$ in industry is commercial technology, and has been ongoing for decades TRL is clearly 9 for this example. But ship transport in the l scale needed for CCS, has not been proven, and the TRL level is in the area of 3-5. There are issues regarding offshore offloading and also pre-treatment before transport that need further investigation and research.

Industrial scale pipeline transport of petroleum products has been practiced for a long time, both onshore and offshore. A number of onshore $CO_2$ pipelines are operating in the US, and also offshore pipeline $CO_2$ transport is taking place on the Norwegian continental shelf. TRL for $CO_2$ pipeline transport is therefore at the level of 8-9.

Offshore storage of $CO_2$ is well known from the year long experience of the Sleipner and Snøhvit projects. Onshore storage (apart from $CO_2$-EOR) has been demonstrated for instance at In-Salah in Algeria. The TRL for $CO_2$ storage is assessed to be in the area of 5-9. ,

It is a challenge to assess TRL levels for comprehensive technologies like capture, transport and storage, because the technologies are varied and parts contain more or less the whole scale of TRL. As a short summary; almost all the different equipment parts have been proven and are in TRL 9, but the system as a whole is not proven in a commercial scale even if the equipment parts is used for other applications today. In this report, a general impression of the levels is discussed, but there might be specific parts under each technology that are higher or minor on the TRL scale.

## CCS implementation barriers

### Economic incentives and drivers

This is an important issue and can only partly be addressed by CCS technology improvements giving lower costs as described above. Mechanisms should be established to facilitate CCS both in industry and power production. The national states need to take on the responsibility to establish and finance the CCS infrastructure. Most Nordic industries are exporting to global markets and proper measures are required to maintain their competitive position and avoid carbon leakage, which will be a risk if one or more of the Nordic countries undertake a leadership role in CCS.

### Legal framework and political will

It will be essential to maintain the CCS issue at the top of the political agenda at both national and international levels. This is fundamental with regard to the establishment of the required legal framework and development of international cooperation to launch the first CCS full chain projects in the Nordic countries. It is also essential to reduce long term uncertainty and provide predictability for the Nordic industry including power producers. The Nordic governments will need to take an active part as well as responsibility regarding transport and storage infrastructure to share risk and economic burden. Long term liabilities will be a key issue.

## Public awareness and acceptance

Generally speaking there is little or limited knowledge and awareness in the public regarding CCS. Experiences from $CO_2$ storage projects in Denmark, Germany and The Netherlands in the past have revealed significant resistance to onshore $CO_2$ storage. Clear and open communication of the importance of CCS as well as of uncertainties and risks involved is essential.

In order to build confidence and trust with the general public and those responsible for CCS implementation a number of issues needs to be addressed:

- Information to the public and decision makers on possible outcomes if CCS is not implemented. Alternatives and their impact on the industry and power production need to be discussed, and CCS should be put in context with other $CO_2$ mitigation options.
- Pros and cons for CCS in local communities and what CCS means to employment

## Organisation and business models for the CCS chain

CCS deployment in the Nordic countries is a complex challenge involving many interests and stakeholders. The governments, industries and power producers have to take on the main responsibilities leading to the implementation of CCS. The role of the research community would be to provide a scientifically sound basis for decision makers, and to take part in communication and dissemination activities. A key issue is to find proper ways of risk sharing and acceptable economic exposures. Good organisation and business models with clear responsibilities must be developed and established. This will help pave the way for the “first mover” and put more pressure on others to follow suit.

# Summing up recommended R&D tasks

To promote CCS implementation in this context the capture technology must be suited for each individual plant/site and have an energy supply which gives a more cost effective solution than current technology can provide. Post-combustion technologies seem the best short term solution for existing plants and further R&D and studies are required to qualify low energy absorbents/adsorbents, other novel gas separation technologies and cryogenic technologies. Further to improve our scientific understanding of capture mechanisms, modelling capabilities and basic thermodynamic and kinetic data.. Efficient capture of biogenic $CO_2$ emissions and innovative concepts can provide carbon negative solutions and should be developed.

Even though pipeline and ship transport of $CO_2$ are well established today, development of an optimal $CO_2$ network and infrastructure as part of the CCS chain is a challenge in the Nordic countries. Large scale transport solutions will probably include mixed transport modes also from a ramp-up perspective. Technology development is needed for offshore unloading of $CO_2$ and injection into geological storage formations.. Contaminants in the $CO_2$ will require studies and tests in order to secure safe and optimal material choices. Dynamic and transient situations should be modelled to find safe designs and process control solutions. Better thermodynamic data for impure $CO_2$ should also be obtained.

Long term, safe, reliable and publicly accepted offshore $CO_2$ storage is crucial for Nordic CCS deployment. For many potential storage sites more and better data are needed to understand storage mechanisms, dynamic $CO_2$ reservoir behaviour as well as suitable monitoring techniques and mitigation measures in the event of $CO_2$ leakage. More injection pilots should be executed to build knowledge needed for injection well design and optimal location determination. $CO_2$ driven EOR is still an opportunity in the North Sea which potentially could change the economics of CCS in a positive direction and should be studied further. A more basic understanding of $CO_2$ mechanisms for releasing more oil in the various reservoirs and innovative concepts for offshore solutions is required.

In order to close many of these knowledge gaps a closer cooperation between academia/ research institutes and the various industries and power producers is required. Finding adequate incentives to promote such cooperation projects is therefore essential.

## Concluding remarks

To prepare Nordic industries and fossil based energy producers for future CCS deployment will play a vital part in sustainable development. Through focused R&D within CCS and two pioneering, large scale industrial storage projects a competence and experience base are being developed. This gives a good platform for responsible, safe and successful technical implementation of CCS in the Nordic countries.

However, there are still significant knowledge gaps to be closed, especially to reduce energy needs and to reduce costs in $CO_2$ capture processes. It is also important to build confidence in $CO_2$ offshore storage and find optimal solutions for transport. This is true for both ramp-up situations and long term performance. Demonstration projects both for $CO_2$ capture and storage need to be developed proving our readiness for widespread CCS deployment. In particular, integrated projects encompassing the whole CCS chain, are needed.

By maintaining and improving our CCS competence the Nordic countries will be prepared to face the needs as the CCS industry establishes and grows. Political courage and will must provide the proper framework to overcome current barriers and make CCS happen.

## Acknowledgements

This report is based on the work in the project NORDICCS, and in particular the work shop in Copenhagen 23.April 2015. Thank you to all the participants for their effort and inputs.

A special thanks to Karen Lyng Anthonsen, Geus and Halvor Lund, Sintef, for your efforts and comments during the work of this report.

NORDICCS is supported by the NORDICCS Centre, performed under the Top-level Research Initiative $CO_2$ Capture and Storage program, and Nordic Innovation.

The authors acknowledge the following partners for their contributions to the NORDICCS centre: Statoil, Gassco, Norcem, Reykjavik Energy, $CO_2$ Technology Centre Mongstad, Vattenfall and the Top-level Research Initiative (Project 11029)

## References

[1.] NORDICCS report WP 4 : D. 4 .1.1203 $CO_2$ capture – a state-of-the art assessment,

[2.] WP 4 NORDICCS " CO2 storage Atlas"

[3.] NORDICCS report WP 5:Kjærstad.J et al. "D20 Recommendations on CO2 transport solutions, 2015

[4.] P. Aursand, M. Hammer, S.T. Munkejord, Ø. Wilhelmsen, Pipeline transport of CO2 mixtures: Models for transient simulation, International Journal of Greenhouse Gas Control, Volume 15, July 2013, Pages 174-185, ISSN 1750-5836,http://dx.doi.org/10.1016/j.ijggc.2013.02.012.

[5.] John C. Mankins, white paper "TECHNOLOGY READINESS LEVELS" 1995

[6.] Folger,P. "Carbon Capture: A Technology Assessment", ,July , 2010