Large-scale storage of CO$_2$ on the Norwegian shelf

Enabling CCS readiness in Europe

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Abstract

Fast implementation of CO$_2$ storage on a large scale is needed to meet the international targets on reduced CO$_2$ emissions. In the absence of a commercial market, Norwegian R&D actors have formulated a vision that implies storage of more than 10 million tons CO$_2$ per year on the Norwegian shelf. The purpose is to restore the momentum of CCS research, to direct and coordinate on-going and future efforts to develop the technology, and to motivate industry and authorities to engage in a more forceful schedule for CCS deployment. Based on a review of technology needs, a case-based study is proposed to apply and improve the knowledge and technologies needed by industry to undertake field development studies by 2018.

Keywords: Large scale CO$_2$ storage; the Norwegian shelf; technology gaps; show stoppers; method validation; upscaling.

1. Introduction

Carbon capture and storage (CCS) has been on the international agenda as a potential measure to reduce CO$_2$ emissions since early 2000. Around 2005 great optimism prevailed regarding rapid implementation of CCS. There was a substantial focus on climate change and high political ambitions for resolute action. The confidence in CCS
as an important part of the solution was strengthened by high expectations for CO₂ EOR. However, an ambiguity has emerged in Europe regarding CCS deployment: there is public doubt in many countries regarding how safely CO₂ can be stored, the costs of implementing CCS on a large scale prove to be high on the short term, and the lack of international agreements and weak policy signals make the industry reluctant to commit to heavy investments. The situation is further complicated by the global financial crisis and the fact that the lead time for implementing CCS technology, exploring potential sites, licensing and commencement of operation is significant (4-15 years) [1]. Due to the high cost of CCS and small economic incentives some countries, e.g. Germany, have promoted alternative electricity supply by subsidies to wind and photo-electricity. These programmes have however, become very expensive and the potential for wind is becoming exhausted. The programmes also demonstrate that the fluctuation in supply of renewable energy resources depend on solid base load power sources such as fossil power plants. In other parts of the world like USA, China and the Middle East, the prospect of enhanced oil recovery (EOR) drives the implementation of solutions for CO₂ capture and storage. Thus, after the start of the Sleipner and Snøhvit CO₂ storage projects in 1996 and 2008, respectively, the momentum for new industrial CO₂ storage projects is reduced. This causes a weak market pull that subsequently can affect research to become less focused, more fragmented and without the necessary determination.

Despite the slow progress in large-scale integrated CCS projects in Europe, CCS remains critical for the long term. UN (IPCC), EU, Norway and many other national governments have adopted a target of 2 °C limit on the global temperature increase (2 Degree Scenario, 2DS). IEA [2] states clearly that CCS is the only technology that can allow industry to meet emission reduction targets. Without CCS the additional investment needed in electricity production will increase by 40 % - amounting to USD 2 trillion over 40 years. IEA also states in the same report that there are CO₂ capture technologies commercially available, but there are CO₂ storage issues remaining to be solved and there are challenges in integrating CCS technologies into large-scale projects. To enable CCS as a CO₂ mitigation technology urgent actions are needed, because the emissions continue to increase and pivotal solutions are not yet ready for implementation.

2. Measures for advancing CCS deployment

To meet the UN and EU climate policy goals, there is a growing recognition that we need to scale up CCS deployment. Large volumes of CO₂ must be stored by 2050, posing tough requirements with regard to storage capacity and efficiency. Global deployment of CCS can be more effectively met by up scaling to fewer and larger storage sites, collecting CO₂ from multiple capture projects and integrated transport systems. To reach 2DS, globally stored volumes of CO₂ must equal 2.4 Gt/year in 2030 and 7.8 Gt/year in 2050. In comparison; the total capture capacity of the large-scale integrated CCS projects currently in operation is about 0.023 Gt/year and the capacity of plants under construction is about 0.014 Gt/year [1]. Most of these projects have EOR as the primary storage option and the net CO₂ reduction may be lower than what is actually captured, since some of the CO₂ will be produced back to surface. This confirms that a more forceful approach is needed to have a significant impact on the steadily growing CO₂ emissions.

Effective global deployment of CCS requires fast implementation of adequate measures. Suggested actions are:

- Develop fast track demonstration projects in parallel with research and development to speed up the implementation process and at the same time close critical knowledge gaps
- Develop large scale projects to ensure cost-effective storage of large volumes of CO₂ in few storage sites, which also can minimise the potential conflicts (public perception, conflict with other interests)
- Identify possible EOR targets to improve overall economy.
3. CCS in the Norwegian perspective

In the Norwegian perspective, large-scale storage of CO₂ is interesting for several reasons. Firstly, mitigation of CO₂ emissions in Europe implies subsurface storage of large volumes of CO₂, and there is currently little support for storing CO₂ onshore in Europe. There have been several studies on the storage capacity in the Norwegian North Sea [3][4][5] indicating a storage potential in the range of 72 to 500 Gtonne CO₂ which should be seen in context with the 2 Gtonne/year emission of CO₂ from point sources in EU-27. By building on Norway's expertise in offshore oil and gas industry, Norway can offer both technology and storage capacity offshore that can play a significant role in resolving the CO₂ emission problems in the region. Norwegian authorities are developing a plan for offshore storage of CO₂ from onshore gas power plants in Norway, but no decisions have yet been made. If Norway is able to make the business case of CO₂ storage, CCS can become a commercial industry in Norway and at the same time be an enabler to CCS in the EU.

A CO₂ storage infrastructure may also enable supply of CO₂ for EOR in mature North Sea oil fields. From four decades of CO₂ EOR in USA, CO₂ has proven to be the most effective injection gas and has been regarded as the standard tertiary EOR method being applied in 114 on-going projects [6]. In the world's largest CO₂ EOR project, the Wasson Denver Unit, more than 90% of the injected CO₂ is actually permanently stored and also for other CO₂ EOR projects in North America the majority of injected CO₂ is stored [7]. The environmental effects of CO₂ EOR can be significant. This is illustrated by [8], were CO₂ injection was studied for 18 Norwegian and 30 UK water-flooded oil fields. The results showed that the projects gave a net storage of CO₂ even if the CO₂ from combustion of the EOR oil produced was included. [5] also emphasizes the potential of CO₂ for EOR in the North Sea, but implementation is time critical to fit the window of opportunity of aging oil fields. To develop an effective CO₂ – EOR infrastructure for the Norwegian North Sea oil fields, large volumes of CO₂ are needed within relatively short terms. It is a fact that CO₂ from Norwegian capture plants cannot meet the required need and that the life-cycle of a carbon capture and transport system has a much longer perspective.

Secondly, CCS may be instrumental for securing the future value of the petroleum industry as well as remaining oil and gas resources. The report published for the European Climate Foundation in 2012 [9] points to CCS as a means for avoiding carbon lock-in and securing the future value of natural gas. The report Unburnable Carbon [10] paints an even more challenging scenario, stating that the 2/3 of remaining proved reserves are unburnable and that only a small amount of fossil fuels can be burnt unabated after 2050 to achieve the 2DS. In the long-term transition to a low carbon economy, CCS may be a measure to secure fossil reserves and limit the potential impact of the systemic risks that threaten the stability of the financial markets.

Finally, considerable efforts are being put into CCS research and demonstration of CCS technology. The CLIMIT program is established by the Ministry of Petroleum and Energy to promote technology for carbon capture and storage. It aims to accelerate the commercialisation of CCS through economic stimulation of research and development (administered by the Research Council of Norway), as well as testing and demonstration (administered by Gassnova) [11]. A large portfolio of projects, including public and private funding, is conducted within CLIMIT since 2005, and has resulted in a comprehensive knowledge and technology base on CCS.

4. Setting the ambitions for CO₂ storage development

To underpin and accelerate the development and operationalization of CCS technology, the research community must concentrate on the critical knowledge gaps and define a schedule that is more ambitious than before. In June 2012, Gassnova and the Norwegian CCS research centres, BIGCCS [12] and SUCCESS [13], formulated a vision that can contribute to directing and coordinating national research on CO₂ storage:

The Norwegian research community will contribute in developing the knowledge and technology necessary to enable large-scale storage of CO₂ (>10 Mt CO₂/year) on the Norwegian shelf by 2018. Particular attention is put on the use of CO₂ for EOR, harvesting from the Norwegian petroleum expertise and business opportunities related to CO₂ storage.
On this basis a project was initiated, to investigate if an industry-political vision can take the role as the demanding "customer" and thus, contribute to aligning the Norwegian R&D community and direct their efforts towards effective utilization of Norway’s CO2 storage capacity. The objective was to prepare the ground for adequately addressing R&D issues critical to allow detailed planning of large-scale storage of CO2 by 2018. An important part of the work was to identify the key geoscience and petroleum technology gaps related to large-scale CO2 storage.

5. Storage sites suited for large scale CO2 storage

There are several large reservoir candidates, but most of them are immature with respect to a decision on large-scale CO2 storage within a five years period. For many of the candidates, large reservoir sand bodies may have been identified, but injectivity as well as cap rock integrity may be unknown. To set the frames for the technical discussions in the reported project, a few prospective large candidates that could be used early were discussed. The sites should represent different generic storage solutions with various characteristic features and were used to illustrate the span of challenges and hence, stimulate the work processes to cover all critical matters. In a future study, one of them may serve as a case suited for feasibility studies and technology/model validation:

**Utsira formation:** The successful storage project on Sleipner, where 14 million tons CO2 has been injected into the Utsira formation, has illustrated some of the exceptionally good reservoir properties of this formation. The Utsira formation along with the Miocene sands just below it (Skade, Eir) will therefore be one of the most obvious candidates for large-scale storage. Further extensive exploration (explorations wells) will not be needed before the first injection and water production wells are drilled. The Sleipner storage project has demonstrated effectiveness of 4D seismic to visualize the CO2 distribution.

**Frigg depleted gas field:** The second most mature storage site that could be available for large-scale storage is the Frigg area depleted gas reservoirs. The reservoir properties are well known after decades of gas production and there are also interesting sands below the Frigg gas field that may provide flexible options for development of a storage project. Water production from this formation must be carried out with some care because initially there was an oil zone between gas cap and aquifer.

The **Byrne/Sandnes, Johansen and Gassum** formations are examples from a large group of potential formations that might be prospective candidates for storage, but only on a time-horizon outside the scope of this study. Since large-scale capacity in the shallower formations (Utsira, Skade, Frigg) is much more readily available, the focus should be directed to these reservoirs for a large-scale storage project.

6. Identified technical and non-technical challenges

A collaborative process was conducted among major Norwegian CCS research institutions during fall 2012 to review the main challenges posed by the formulated vision on large scale CO2 storage. The work resulted in identified key geoscience and petroleum technology gaps related to large-scale storage [14]. The main conclusion is that there seems to be no technical show stoppers related to large-scale CO2 storage, but efforts should be made within specific areas to validate and to some extent advance the existing knowledge, technology and methods, with respect to both accuracy and reliability. Improved confidence in the technology is imperative for the industry facing major investment decisions if large scale CCS is implemented. Also, public authorities, politicians, interest groups and the general public must be convinced that CCS is a safe and long term solution for reducing CO2 emissions. In addition to the technical challenges legal, regulatory and political hurdles must be overcome, such as an adequate set of rules related to CO2 transport across national borders. Finally, new business models are needed to enable development and operation of large scale CO2 infrastructures.

**Reservoir capacity estimation and long-term behaviour**

To estimate reservoir capacity and predict the long term behaviour of CO2, **reliable simulation tools** are essential. Available data are often sparse, and it is expensive to provide additional data. Thus, reliable simulation models, incorporating the dominating processes of CO2 injection and storage, are a prerequisite to provide the information needed to decide on CO2 injection. Identified areas where further development and validation of models are needed
include prediction of long term migration of CO₂, understanding of trapping mechanisms including capillary trapping, solubility trapping and topographical trapping, tools for improved history matching combined with extended monitoring, and reservoir pressure estimation. Research is on going and should be strengthened to improve the technology on the longer term. To enable CO₂ storage readiness within 2018, full reservoir simulations of CO₂ injection in selected targets should be conducted to demonstrate applicability of existing models and simulation tools and pinpoint critical limitations that must be addressed. By benchmarking tools on selected case(s), conducting sensitivity studies wrt geological properties and processes, and investigating if history matching in the injection period reduces uncertainties on long-term predictions, the available technology can be verified.

**Geological seal integrity of large-scale CO₂ reservoirs**

Seal integrity depends on fundamental mechanisms that must be understood to make reliable predictions, and the scarcity of data (core material, fluid samples and other types of well data) makes the task more challenging. Three research topics have been identified as the most pertinent knowledge gaps for seal efficiency, in the context of large-scale CO₂ storage being ready for commercial action by 2018.

- **Reactivation of seismic and sub-seismic faults/fractures**: Improved understanding of deformation mechanisms, stress, and safe upper limits for pressure build-up from CO₂ injection is needed and can be obtained by 2018.

- **Overburden baseline assessment by coring, testing and fluid sampling and analysis**: For sites where limited data is available a dedicated program for coring, testing and fluid sampling of the overburden, fluid and solid characterization, including baseline and compartment assessment, should be run. The data acquired must be on a basin scale and integrated with regional seismic data, enabling improved up scaling and risk prediction of seal properties. To enable CO₂ storage by 2018, mature sites where sealing characteristics are known should be prioritised. This is reflected in the preliminary selection of storage candidates.

- **Workflow for monitoring and simulation**: This implies the establishment of a geomechanical model, consistent with integrated geophysical/instrumental/geochemical monitoring data providing the necessary constrains for the reservoir simulation. This will also enable improved risk assessment, including early warning definitions and suggestions of remediation actions.

**Monitoring Technologies**

The objective for monitoring the injection of CO₂ is to ensure optimal and safe operation, provide input for update of the site geology and monitor the integrity of the storage. Technology and methods for monitoring of CO₂ are available. However, improved technology and methods are beneficial to make operations faster, more accurate and cheaper.

- **Fast results**: To be useful for a CO₂ injection operation the monitoring result should be available as fast as possible. Some methods (pressure, tracers) might be analysed quickly, or even in real-time (micro seismic and pressure gauges), to provide feedback on the injection, while others (e.g. seismic and CSEM) require several months for interpretation.

- **Accuracy and detection limits**: While geophysical methods typically are developed for the petroleum industry to detect large volumes of petroleum resources, CO₂ monitoring requires detection of small changes (leakage detection) or accurate volume estimates. The sensitivity of the methods may vary between sites. In the early phase of injection it is possible to test detection limits in situ by gradually injecting small amounts of CO₂ while simultaneously conducting monitoring surveys. This can give an accurate assessment of the sensitivity of the data and indicate the feasibility of the method. Integration of different monitoring methods, e.g. gravity, resistivity, seismic and micro-seismicity by jointly inverting the data can also improve sensitivity.

- **Low-cost monitoring**: Current CO₂ storage projects are monitored mainly for research, and not from an operational and safety aspect. In a full scale CO₂ storage project the focus will be on cost-effective methods, particularly for a long-term program. They must to some extent be developed during the course of the injection project because the performance of various methods is site specific and need to be tabled for the site.
Drilling and well construction
Wells similar to those of a long term large scale CO₂ storage project on the Norwegian shelf are drilled and completed according to standard procedures in the oil and gas industry. The focus should be to what extent wells are suitable for long-term CO₂ storage and the differences imposed by it. The key gaps are:
1) Need for flexible, smart and robust well design;
2) Evaluation of current well barriers and their adaptation to CCS industry;
3) Development of leakage remediation measures and fast response teams;
4) Creation of best practices and legislations for all phases of well life including abandonment;
5) Development of standard testing procedures;
6) Cost reduction and efficiency on all aspects of drilling and well;
6) Possibility to use cheap and smart exploration technologies, like, for example, Badger explorer.

Large-scale development solutions and infrastructure for CO₂ storage
Development of design specifications for offshore CO₂ injection as well as identifying candidate oil fields for primary use of CO₂ for EOR are both time critical activities. Therefore, possible storage site(s) should be identified as soon as possible to enable the planning and construction of a large-scale infrastructure. Even without any delay, it will be challenging to meet the ambition to decide injection of large amounts of CO₂ by 2018.

Based on the discussions in the reported project, two technical gaps are identified that should be closed by 2018.
• Development of design specifications for offshore CO₂ injection into saline aquifers, including
  o Early decision basis for overall development solution (e.g. platform, subsea, or combinations)
  o Simplified requirements and solutions for CO₂ injection development
  o Simplified solutions for CO₂ transportation (e.g. pipeline and ship/barge)
  o Localization and construction of infrastructure (e.g. CO₂ sources, storage capacity – aquifer, EOR)
• Implications of using CO₂ as a primary method for oil production: CO₂ for EOR has normally been considered as a secondary or tertiary recovery method suited mainly for tail production in the North Sea. So far, no such projects are implemented largely due to economy, combined with in some cases unfavourable reservoir conditions, and uncertainty regarding regularity and amount of CO₂ supply. If a large-scale CO₂ infrastructure is in place, sufficient CO₂ for large-scale EOR may be secured

In addition two non-technical gaps were identified:
• Business model for large-scale CO₂ infrastructure: Defining an optimal business model for constructing and operating a large-scale CO₂ infrastructure is a necessary step for moving the idea of a large-scale CO₂ storage towards realization. An important issue is to establish a business model for the entire CCS value chain. Securing a stable supply of CO₂, in particular for EOR purposes, will be an important issue. Part of this is also to the question of infrastructure sizing, particularly relevant for pipelines, and who is to pay for oversized or unused pipelines and other infrastructure in the making.
• Regulations and policy: International regulatory work is progressing, but still there are several issues that are not resolved. For the time being one such issue relates to CO₂ transportation across international borders. Even though it is possible for Norway to enter into bilateral agreements with countries for supply of CO₂, this issue will be time consuming and is a potential showstopper within the time frame of 2018. Another possible issue is how to regulate new industry dealing with infrastructure and injection of CO₂.

7. Strategy to enable large scale CO₂ storage – the way ahead

One immediate effect of the reported project is that the CLIMIT call for research projects on CO₂ storage published in May 2013 refers to the final report and it requests that project proposals are developed within the topics identified as critical to enable large scale CO₂ storage on the Norwegian shelf [15]. Thus, it is expected that the portfolio of national R&D projects can become more aligned towards the above vision. Moreover, by prioritizing projects that are complementary with respect to the identified needs, the Research Council can
contribute to providing a more complete knowledge and technology base, covering fundamental issues considered important to solve before 2018 and beyond.

Besides the focus on continuous R&D to advance CCS technology, there is a need to strengthen the efforts to validate and improve the current knowledge and methodologies. The reported project recommends establishing a collaborative feasibility study over 2-3 years to close the gap between current research and CO2 storage demonstration. The ambition is to provide the knowledge and technology to enable efficient and safe storage of large amounts for CO2 at a lowest possible unit cost and thereby contribute to fulfilling the vision. The planning of such a study is well underway, and a proposal for a first phase of the study is developed. The idea is to use one or more selected potential CO2 storage sites on the Norwegian shelf as case and structure the study similar to a Plan for Development and Operation (PDO) for an actual CO2 storage site. This is to ensure alignment and further development of the knowledge and methodologies needed by commercial industry to undertake a field development study by 2018.

Relevant tasks of the study include:

- Estimate storage capacity of case(s) and choose appropriate storage rate
- Plan optimal placement of minimum number of injection and production wells
- Investigate options for EOR
- Outline a infrastructure for transporting CO2 from main sources in Europe, possibly with branches to cover EOR needs
- Propose a simple plan for operating the transport and storage system
- Develop a cost effective monitoring plan
- Estimate investment and operation costs including long term monitoring

The selected approach will enable the identification of limitations in the knowledge base and methodologies, and particular effort can be put into investigating these challenges. Some gaps may be of a character that they should be pursued in a separate R&D effort, but the majority will be explored as part of the study and by the partners involved. Some foreseen challenges are related to:

- handling site specific differences/geo
cological variability in a robust manner. According to ZEP [16] the location and type of field, reservoir capacity and quality are the main cost determinants.
- up scaling of methods and technologies from research/pilot scale to demonstration and full scale. The viability and effectiveness of the technologies with respect to reliability, accuracy, practicalities and cost, when handling an amount of CO2 relevant for commercial projects must be assessed.
- investigate business opportunities and viable strategies for ramp up of CO2 storage on the Norwegian shelf.

The proposed project will also investigate non-technical gaps, e.g. business models for large-scale CO2 infrastructure, recommendations for an international regulatory framework and public communication. However, the main task is to address technological perspectives complementing the scope of projects initiated by oil companies, commercial businesses and governmental bodies, and to secure that on-going and new research is coordinated and relevant for fulfilling the vision. The project may also provide a context for future field labs, pilots and demonstrations. The planned study will represent a common framework for the Norwegian research community, where the research institutions may collectively contribute to closing the scientific gaps. However, the initiative depends on close interaction with both industry and authorities, and an important initial task will be to discuss their roles and possible contributions. For instance, access to site data and experience from national CO2 storage projects is essential, and knowledge on how the project should be organized and managed in order to be relevant for industry is imperative. It is highly relevant to seek international collaboration. Several European research institutions have been focusing on CO2 storage over many years, and knowledge sharing and cooperation enable optimal use of resources. To investigate opportunities in CO2 for EOR, it is also relevant to seek collaboration outside Europe.
8. Conclusion

Large CO₂ storage capacity and expertise on offshore oil and gas operations are Norwegian strengths that are relevant for implementing CCS. In addition, CCS may become essential to secure the future value of Norwegian petroleum reserves. Despite the urge to develop low carbon solutions, it is hard to build the business case for CCS and the industry is reluctant to invest. By formulating a common vision for large scale CO₂ storage on the Norwegian shelf, it is anticipated that CCS research can restore its momentum despite the current absence of the demanding "customer". Through common efforts to identify technology gaps and define strategies for closing them, the research community can regain motivation and ensure alignment of the projects aiming at developing safe and cost-efficient solutions for CO₂ storage. Over the last year, major Norwegian research institutions have pinpointed critical gaps that must be overcome to implement large-scale CO₂ storage. A plan is underway to conduct case studies based on selected storage sites to apply and further develop the knowledge and methodologies needed by industry to undertake field development studies by 2018, and thus enable efficient and safe storage of large amounts of CO₂ (>10 million tons/year). This approach could help motivate both industry and authorities to engage in a more forceful schedule for CCS development and deployment. By taking such measures, Norway may also stimulate other nations to mobilize stronger in the combat to reduce CO₂ emissions through CCS.

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