Northern Lights: Screening and maturation of CO_2 storage prospectivity

Diego Vazquez Anzola[a], Renata Meneguolo[b] & Silvia Kassold[b]

[a*] *A/S Norske Shell, Tankvegen 1, 4056 Tananger, Norway*
[b] *Equinor ASA, 4035 Stavanger, Norway*
**Corresponding author (e-mail: diego.vazquezanzola@shell.com)*

Abstract

The Northern Lights project is the transport and storage part of the world's first full value chain CCS project where CO_2 from onshore industrial emitters will be injected and stored offshore, in the northern North Sea (western coast of Norway). Storage resources, containment risks, information availability and development costs are critical factors in the identification and maturation of a viable geological storage site, and are challenging to objectively assess and compare for different geological storage concepts.

The subsurface candidates evaluated in the Northern Lights project included several geological storage concepts such as a structural closure (Smeaheia), a depleted field (Heimdal) and a semi-regional sloping saline aquifer (Aurora).

During the studies on the three potential storage sites, a workflow was created that incorporates a combination of assessment parameters suitable for benchmarking, which supported the investment decision for the Northern Lights CCS project by the three partners Equinor, Shell and Total.

Of the three candidates, the Aurora area represented the most prospective site because of its larger potential for high resource scalability. Key data gaps were addressed by high-risk pre-investments in an exploration well aimed at confirming and maturing the CO_2 storage resources.

A set of tools are hereby proposed to highlight uncertainties, risks and opportunities when screening and ranking CO_2 prospective storage sites. These tools are to be considered an ever-green and evolving philosophy, which form the foundation of what is considered most relevant when screening and building a portfolio of prospective CO_2 geological storage sites.

First words

In order to mature reliable geological storage sites, in terms of sufficient storage resources, manageable risks and development costs, a consistent set of screening criteria are necessary. These criteria are to be implemented as ranking tools aimed to complete a thorough prospectivity evaluation for CO_2 geological storage resources before any investment of resources, including manpower, is decided.

Ringrose (2020) provides an overview of previous publications associated to "Site integrity and risk management" of CO_2 storage projects. Publications such as the IEAGHG (2009) report and Pawar *et al.* (2015) define a risk management framework that is extremely useful to describe, manage and communicate site specific risks and mitigation plans. Finally, estimation of the storage volumes (resources) has been defined for different storage types (Thibeau *et al.*, 2014, Bachu *et al.*, 2007). However, these are not complete or appropriate to identify and screen suitable geological sites for CO_2 storage. Given the lack of specific established methodologies this article aims to propose a set of tools to highlight uncertainties, risks and opportunities when screening and ranking CO_2 prospective storage site.

It is recognized that the tools hereby proposed are strongly inspired by the experience of the Northern Lights subsurface team, which carried out a detailed analysis of three (3) very different prospective CO_2 storage sites. These tools are by no means finalized or completed but are considered an ever-green and evolving philosophy aiming to form a foundation of what is considered most relevant when screening and building a portfolio of prospective CO_2 geological storage sites.

Despite the screening parameters or criteria taken into consideration are often intertwined and interdependent, this article is an attempt to categorize and streamline a systematic process to evaluate potential CO_2 storage sites.

Northern Lights: A full-scale CCS project

In a Decarbonization and Energy Transition world, Carbon Capture and Storage (CCS) is a proven technology that is highly needed to meet the emissions reduction commitments of the Paris Agreement. This is clearly reiterated in relevant CCS related publications such as Tucker (2018) and Ringrose (2020).

The recent sanction of the Northern Lights project by the three (3) partners (Equinor, Shell and Total) is considered a success story of an emerging and very complex business model that is key for the future strategic position of the Energy sector in the transition to a decarbonized industry.

The intention of the Northern Lights project, is to build a strong partnership with the Norwegian government to contribute in their shared ambition to build a CCS project that would stimulate the necessary development of CCS so that long-term climate targets in Norway and the European Union can be attained at a lowest possible cost.

The Northern Lights project scope includes ship transport, onshore temporary storage, pipeline transport to an offshore injection well, and injection of CO_2 for storage in the Aurora site, within the Exploitation License 001 (EL001). A full chain schematic is shown in Figure 1 and the locations of the onshore facility, pipeline and injection well are shown in Figure 2.

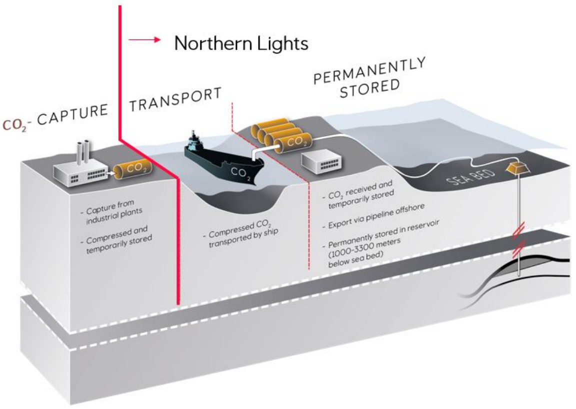

Fig. 1. Northern Lights full chain schematic.

A phased development is planned, starting with a Phase 1 design capacity of 1.5 Mt/y of CO_2 one (1) to two (2) injection wells, and a planned injection period of 25 years, starting from mid-2024. Initially, Northern Lights is planned to receive receive CO_2 from capture sites located in South-Eastern Norway, amounting to approximately 0.8 Mt/y, with the remaining capacity planned to be made available to third parties.

Upscaling ambitions involving a design capacity of 5 Mt/y of CO_2 is planned for Phase 2, which will require additional investment in onshore storage tanks, wells, pump capacity and quays. The present subsea system can be expanded to include up to five (5) injection wells in total.

Prospective CO_2 storage portfolio pre-sanction

Halland *et al.* (2011) provide an excellent starting point for a high-level screening of potential CO_2 storage resources in the Norwegian Continental Shelf (NCS). For the Northern Lights project in specific, three (3) prospective CO_2 storage sites were assessed (Figure 2), encompassing a range of concepts such as structural closures (Smeaheia), depleted gas fields (Heimdal), and a sloping semi-regional aquifer (Aurora).

Figure 2 illustrates the position of the investigated prospects in the northern North Sea, as well as the location of the temporary storage site onshore (Naturgassparken).

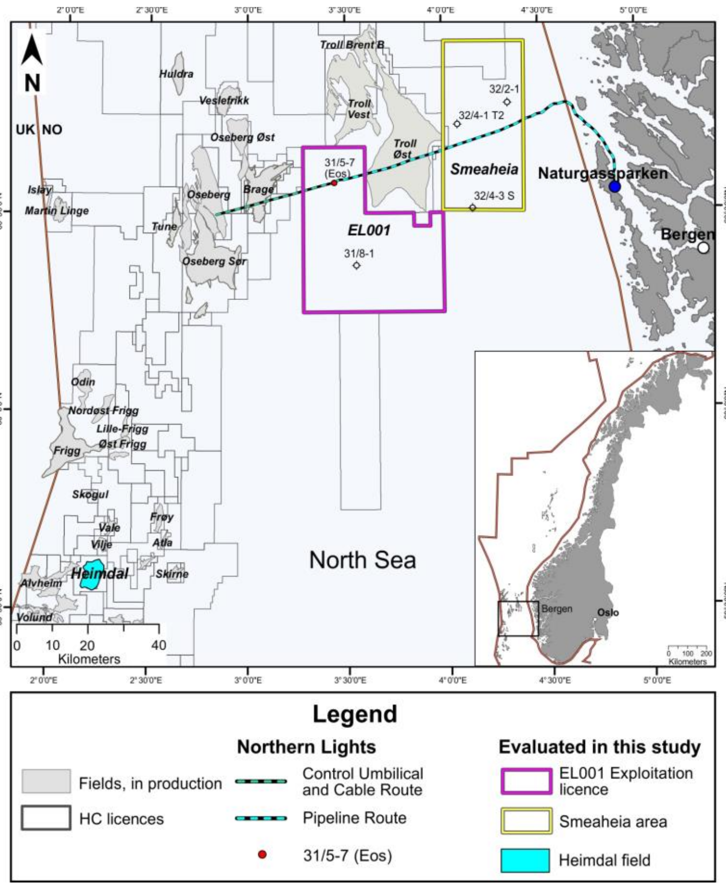

Fig. 2. Northern Lights portfolio pre-sanction.
Location of the assessed potential storage sites in the Northern North Sea, west coast of Norway.

The three (3) assessed prospective CO_2 storage sites (Figure 3) are different in terms of storage concept and therefore presented different challenges and degree of data availability, fundamental to assess the primary and secondary storage units.

The stratigraphic column in Figure 4 summarizes the potential reservoir storage units and main seal systems for the prospects investigated.

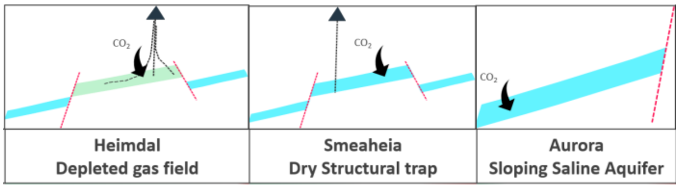

Fig. 3. The three (3) assessed prospective CO_2 storage sites, including a structural closure (Smeaheia), a depleted gas field (Heimdal), and a semi-regional sloping aquifer (Aurora).

The Smeaheia area is characterized by structural closures proven dry by legacy exploratory wells. The stratigraphic unit identified for storage is the Upper Jurassic Viking Group, which includes well-known reservoir rocks (high-energy shallow marine Sognefjord, Fensfjord and Krossfjord fms - Vollset and Doré, 1984) capped by shales of the Heather and Draupne fms, the latter forming a semi-regional cap rock. The storage units and seals are proven in the area by the two existing wells, drilled in 1996 and 2008. Several secondary seals in the overburden were also proven in the area by these legacy wells.

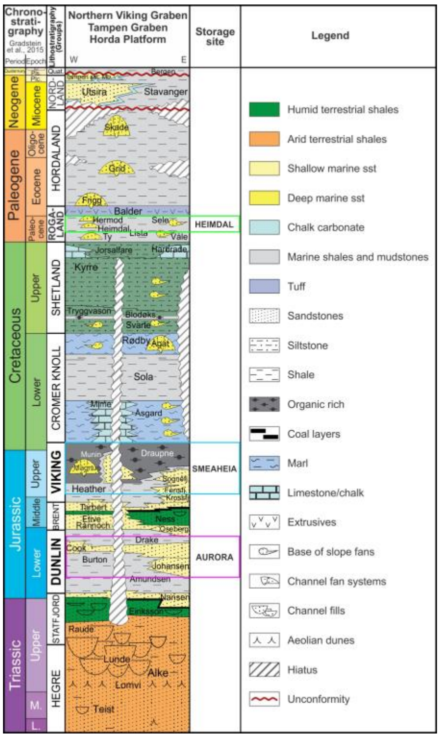

Fig. 4. Stratigraphic column highlighting the storage reservoir units and seal systems for the prospective CO_2 storage sites investigated.

The Heimdal gas field is a four-way structural trap located in the northern North Sea and has been producing for almost four (4) decades from the ~300 m thick sandstone-dominated Paleocene Rogaland Group (deep-water turbiditic Heimdal Formation, Dalland *et al.*, 1988). Currently it is in its tail phase, producing from one (1) of the 12 existing development wells. The primary seal is defined the overlying mudstone-dominated upper parts of the Lista Formation (Zweigel, 2018). The secondary seal is provided by the shales of the Hordaland Group.

The Aurora area is a semi-regional sloping saline aquifer down-dip to the giant Troll hydrocarbon fields (Figure 2). The stratigraphic storage interval is the Early Jurassic Dunlin Gp., characterized by high-energy sandstone wedges (Johansen and Cook formations) encased in marine shales (Amundsen and Drake fms - Vollset and Doré, 1984). Due to its deep stratigraphic position, several overburden units can serve as secondary and contingency seals. The suitability of the Dunlin Gp. for CO_2 storage has previously been addressed by Sundal *et al.* (2013) and Sundal *et al.* (2016).

Besides the different stratigraphic settings and geometrical configurations, the three (3) storage concepts differ largely in terms of data availability and subsequently in degree of subsurface uncertainty. This can represent a crucial factor in the evaluation of a storage site.

The Heimdal depleted field presents a dataset of multiple well penetration and dynamic information, while two (2) exploratory wells were present in the Smeaheia area at the time of evaluation, with different degree of data availability (including 55 m of core in well 32/4-1 T2, Figure 2). In the other end of the range, Aurora is a largely under-appraised area with the closest well penetration of the primary storage units ca. 18 Km away, in the Troll area. Within EL001, well 31/8-1 was drilled in 2011, however did not penetrate the Dunlin Group.

Subsurface core activities for screening and evaluating CO_2 storage resources

Development and appraisal of CO_2 storage resources requires contributions from geology, geophysics, and other subsurface disciplines, combined with a thorough integrated containment risk assessment, which results in a risk-based monitoring plan. Together, these subsurface disciplines are required to mature CO_2 storage resources from prospective to marketable capacity.

The subsurface activities involved in any CO_2 storage assessment can be subdivided into 3 main core activities (Figure 5).

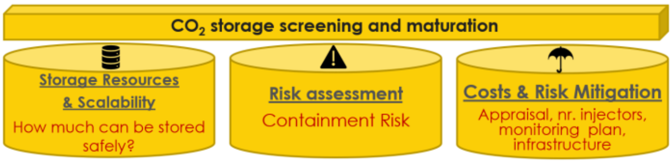

Fig. 5. CO_2 Storage screening and maturation. The 3 Core Activities for CO_2 storage assessments.

Core Activity I – Storage Resources & Scalability:

This core activity includes the characterization of the reservoir storage units using rock properties from available well data. The use of seismic data and geological concepts are determinant, particularly where well data is scarce, e.g., in semi-regional sloping saline aquifers, which are not targeted by hydrocarbon exploration.

Traditional hydrocarbon exploration workflows, including building alternative geological models that match seismic observations and a probability of success (POS) to find an injectable, laterally extensive and monitorable reservoir, are fundamental.

In order to maximize storage resources, and optimize utilization of the planned or existing infrastructure, the rate of capacity increase, or *scalability*, is most relevant.

Scalability is defined as the ability to increase storage and/or injection capacity with additional injection well(s), for a determined period of time. High levels of scalability are achieved by high sustained injectivity per injector well, which is only possible with a large connected pore volume.

Addressing pore connectivity implies the investigation of the aquifer dynamic behaviour, including time-dependent effects on injectivity, containment and ultimately on storage resources.

Confident estimations of CO_2 *storage resources & scalability* are key inputs to define committable and marketable volumes required to build commercial agreements.

Core Activity II – Containment Risk assessment: This core activity includes the identification of potential CO_2 migration paths out of the storage complex. This is done through a comprehensive overburden assessment, which incorporates the characterization of the main seal and any other geological sealing systems. The traditional oil & gas overburden and geohazards assessment workflows, including identification of escape features, shallow faults and permeable zones, are fundamental.

The characterization of the geological seal must also incorporate potential geochemical and geomechanical variations with the presence of CO_2 in the reservoir storage units through time.

The IEAGHG (2009) report and Pawar *et al.* (2015) define a risk management framework that indicate that the way risks are communicated is as relevant as it is to manage them.

In response to this necessity, Pawar *et al.* (2015), Bourne *et al.* 2014 and Tucker *et al.* (2013) have proposed the ''bowtie'' approach as an extremely useful tool to summarize and communicate any geological and man-made (i.e., legacy wells) migration paths that could possibly lead to CO_2 flowing out of the pre-established licensed storage complex. This tool is also used to summarize and communicate the assessed barriers effectiveness and potential consequences and mitigations. The bow-tie method has also been applied to the Smeaheia and Aurora containment risk assessments, the latter is described in Vebenstad *et al.* (2021).

The relevance of legacy wells when selecting an appropriate CO_2 storage side has been particularly highlighted by Tucker (2018).

Core Activity III – Costs & Risk mitigation: This subsurface core activity includes elements associated to CO_2 transport (e.g., pipelines, shipping), but also to the number of wells required to reach a sustained injection rate required to build commercial agreements. These wells could be new or re-utilized.

Moreover, considerations of additional investments for data acquisition (e.g., exploratory or appraisal well), but also other efforts or studies affecting maturation time, are considered part of a risk mitigation plan and associated costs.

A risk mitigation plan includes building a Storage Complex Monitoring (SCM) plan that incorporates activities to ensure containment (storage safety) and conformance (storage effectiveness) by monitoring the CO_2 plume using proven technologies. In addition, the

SCM plan incorporates necessary response actions to address any concern related to conformance and containment.

Site-specific feasibility studies for borehole and surface geophysical monitoring technologies form an important basis for the SCM plan, including applicability of methods such as seismic, gravimetry, and controlled source electromagnetic.

A complete SCM plan is required to build trust and meet requirements authorities and other relevant stakeholders. Logically, a risk-based SCM plan must also be cost effective, hence the close link between Costs and Risk mitigation.

Screening criteria

Different screening criteria have been defined covering the above-mentioned subsurface core activities of a CO2 storage assessment. In order to estimate Storage Resources & Scalability (core activity I), beyond the static pore space volume, the below criteria are considered critical, i.e., if they are insufficient or not present it would result in a serious red flag on the prospective CO2 storage site:

- Injectivity,
- Connected pore volume.

These two (2) criteria define the ability to maintain a minimum injectivity for a determined (long) period of time, which is key for any CO_2 storage site at an industrial scale.

Other criteria such as the presence of baffling or sealing faults, pressure regime, water salinity or presence of hydrocarbons, are also relevant aspects associated to *Storage Resources & Scalability*.

On the other hand, for the *Risk* factor, the screening criteria below are considered critical, i.e., not being present or insufficient would result on a serious red flag on the prospective CO_2 storage site.

- Caprock Integrity / bounding fault seal capacity,
- Monitorability.

These two (2) criteria are combination of elements of core activity II - Risk assessment (e.g., containment risk) and core activity III – Costs & Risk mitigation (e.g., SCM plan or legacy well intervention plan), which results in a holistic view of the residual risks associated to the prospective CO_2 storage site.

Other criteria such as the abandonment condition of legacy wells, fault reactivation risk, natural or induced seismicity, are considered essential input that define the *Risk* factor.

Additional criteria associated to *Risk* that are usually desirable but not always fundamental can be the presence of a structural closure, or hydraulic isolation from nearby hydrocarbon producing reservoirs. Hydraulic communication with freshwater resources, or any interference with other human activities, can be naturally considered showstoppers, particularly for onshore storage sites.

In terms of the *Cost* factor, the below screening criteria are defined based on the core activity III – Costs & Risk mitigation.

- Distance to existing infrastructure or CO_2 source,
- New injectors / legacy well re-utilization,
- Legacy wells requiring intervention.

The distance to existing infrastructure or CO_2 source could directly affect the engineering concept for CO_2 transport, which is logically linked to the *Cost* factor.

Moreover, the number and complexity of new wells needed to maintain a contracted injectivity, or the number of legacy wells that might need to be intervened to avoid possible CO_2 flow leading to emissions to the water column or the atmosphere, can quickly turn into a showstopper for any prospective CO_2 storage site.

A less critical but essential criterion to be considered is the potential of re-utilizing existing infrastructure. In addition, the behaviour of the mobile CO_2 plume, whether it is expected to be constrained within a limited area or not, could significantly affect the costs of the SCM plan.

All of the screening criteria introduced are heavily depending on the *Data Availability* in the potential storage site in order to make a sound subsurface assessment. This includes a confident definition of storage resources and a realistic assessment of the risk picture, which might result in additional investments necessary to improve data availability.

Business attractiveness

The Business Position or *Business Attractiveness* of a CO_2 geological storage site depends upon different cost-benefit factors, that in the Northern Lights project could be approximated to the following relationship:

$$Attractiveness = \frac{Storage\ Resources\ \&\ Scalability}{Risk\ \ x\ Cost} \qquad (1)$$

Storage Resources & Scalability, *Risk* and *Cost* define a series of screening criteria based on the above described subsurface core activities that are most relevant to rank prospective CO_2 storage sites.

A thorough Risk assessment is required (core activity II) in order to establish risk based and cost-effective plans as SCM (core activity III). The *Risk* factor in the *Business Attractiveness* relationship (1) is effectively the estimated residual risk, taking into account a mitigation plan. Consequently, this means that the *Risk* and *Cost* factors are closely related.

Maturation and Business Attractiveness of investigated storage sites

For the Northern Lights project, a Phase 1 capacity of 1.5 Mt/y has been defined, with an injection period of 25 years. A *Scalability* plan includes a design capacity of 5 Mt/y of CO_2 for Phase 2, which will require additional investment in onshore storage tanks, wells, pump capacity and quays. This could lead to the maturation of additional prospective CO_2 storage sites.

Smeaheia dry structural trap: The Smeaheia area is the nearest prospective CO_2 storage site to the onshore facility at Naturgassparken (~50 Km pipeline – Figure 2).

There is one (1) dry exploration well on each Alpha and Beta structures, which are 15 Km apart (Figure 6). Data availability for reservoir characterization of the storage unit is therefore a key strength of this prospect.

The Smeaheia area was initially considered most attractive due to its proximity to the temporary CO_2 storage facilities onshore (Figure 2). Nevertheless, the maturity of the containment risk assessment, including status of the abandoned legacy wells, as well as expected dynamic effects affecting the injected CO_2 in the long term, diminished its attractiveness as a storage site with sufficient scope for scalability (Lauritsen *et al*., 2018).

Lauritsen *et al.* (2018) and Wu *et al.* (2019) indicate that the Øygarden fault, defining the Beta structure, outcrops at the seabed. This evidence does not conclude on the current sealing capacity of this fault, but indicates a recent activity that, together with a juxtaposition profile against a likely fractured Precambrian basin, gives clear warning signs in terms of containment risks.

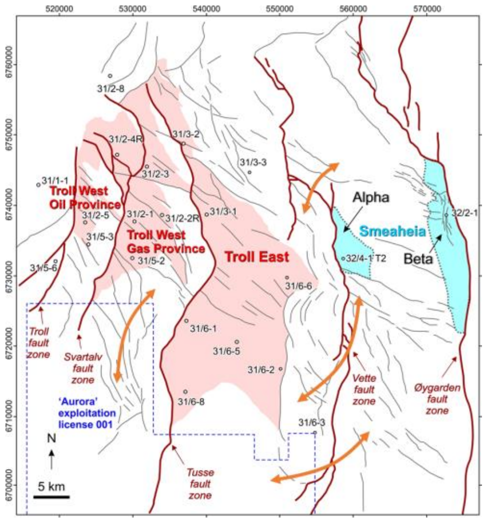

Fig. 6. Regional map of the Horda Platform, offshore Norway, with Aurora and Smeaheia prospective CO_2 storage sites in the vicinity of the Troll field. Main fault zones and most important pressure communication links (orange arrows) are shown. Fault traces are mapped at top Sognefjord Formation. From Wu *et al.* (2019).

The main injection target are the main producing reservoir units in the giant Troll field (Viking Gp. sandstones – Figure 4). Fault seal analysis of the relay ramps along the Vette Fault zone (Figure 6) shows that the Smeaheia area could easily be affected in the future by the pressure drawdown from Troll production (Lauritsen *et al.*, 2018 and Wu *et al.*, 2019). Uncertainty in the timing of the pressure recharging potential from the seabed (through Quaternary sediments and Øygarden fault) is a key added element of uncertainty to the CO_2 *Storage Resources & Scalability* in this prospect.

Moreover, the abandoned dry well in the Alpha structure (32/4-1T2) may require future investments to ensure CO_2 containment.

Smeaheia estimated *Storage Resources & Scalability* might increase if stratigraphically deeper storage units and other structural closures can be incorporated. For instance, a recent exploration well (32/4-3 S – Figure 2) drilled south of the Alpha structure (Figure 6) could add more value to Smeaheia as a CO_2 storage site.

Making use of the relationship (1) and the above-mentioned screening criteria, the estimated *Business Attractiveness* for Smeaheia as a CO_2 geological storage is considered to be Medium, due to a relatively low estimated *Cost* (pipeline length) but also relatively higher *Risk* factors.

Heimdal depleted gas field: Compared to other prospective CO_2 storage sites, the Heimdal gas field (Figure 7) has a unique advantage in terms of data availability: more than 30 years of production history with evidence of a dynamic aquifer responding to production from surrounding fields. A sizable result of storage resources within the trap and in the water leg, and estimations of *Scalability* are therefore dramatically less uncertain than other types of CO_2 storage sites.

Previous studies have indicated its potential as a CO_2 storage site (Zweigel *et al.* 2018), indicating that re-use of existing wells ''proved to be difficult due to their design and well status''; i.e., new wells would be required.

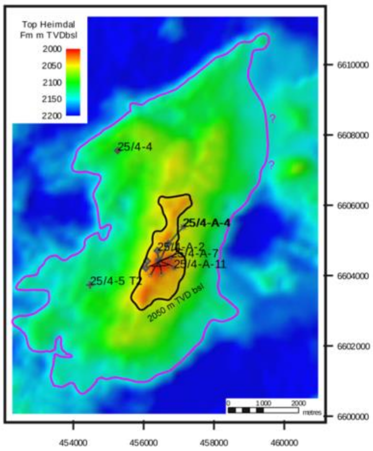

Fig. 7. Map of the Heimdal gas field indicating its 12 development wells and nearby exploration wells. From Zweigel *et al.* (2018).

A much larger distance to the onshore facilities (Naturgassparken), together with conclusions from more recent internal studies, resulted in a decision to postpone the development of this storage site towards later stages of the Northern Lights project, particularly due to the identification of possible integrity issues with two (2) of the legacy wells, which may require future investments to ensure CO_2 containment.

Making use of the relationship (1) and the above-mentioned screening criteria, the estimated *Business Attractiveness* for Heimdal as a CO_2 geological storage is considered to be Medium, due to a relatively high *Storage Resources & Scalability* but higher *Cost* and *Risk* factors.

Aurora semi-regional sloping saline aquifer: Despite having significant uncertainties due to data gaps, the expected high *Business Attractiveness*, based on the relationship (1) and the above-mentioned screening criteria, resulted in the decision to invest on data acquisition and appraisal. More specifically:

- High perceived *Storage Resources & Scalability*: semi-regional sloping saline aquifer expected, ideal for migration-assisted CO_2 storage. Also, third party technical reviews and publications such as Gassnova (2013), Sundal *et al.* (2013) and Sundal *et al.* (2016), indicated sizable CO_2 storage resources.
- Low perceived *Risk* factor, i.e., good quality and monitorable reservoirs in the Dunlin Gp. (Figure 4) in Troll West, and a robust main seal ensuring long term containment evidenced by the existence of the Troll mega closure.
- Relative vicinity to onshore facility Naturgassparken (~100 Km pipeline – Figure 2). Hence a relatively medium to low *Cost* factor.

Available pressure data in the area show that the Viking Group is depleted due to Troll production, with an extended pressure pulse seen by the southern well 31/8-1 (2011), ca. 20 Km away from the Troll field, inside EL001; the Brent Group is depleted probably due to several fields in production and/or due to hydraulic communication between the Brent-Viking groups. Available pressure data acquired in the Dunlin Group until 2012 indicated that there is no pressure depletion observed, thus suggesting that the Drake Formation claystones form a barrier between the depleted Viking and Brent groups to the undepleted Dunlin Group.

Aurora data gaps: Given the uncertainties associated to the expected reservoir properties, sand extension and connectivity, but also associated to the characterization of the overlying Drake Formation as the main seal and possible hydraulic communication to the Troll field, an exploratory well was therefore drilled and tested from December 2019 to March 2020 to address risks associated to:

- Sand presence and quality,
- Monitorability,
- Seal,
- Ability to flow,
- Connectivity,
- Containment,
- Exposure to neighboring hydrocarbon bearing reservoirs.

The estimated *Business Attractiveness* for the Aurora storage site was considered sufficiently high to warrant an additional investment, through an exploratory well, to close significant data gaps.

The scalable way – 31/5-7 (Eos) well results: A series of geological scenarios have been developed pre-well and certain criteria have been set up to make swift decision to decide on the success of the 31/5-7 (Eos) exploration well and by that the success for the continuation of the Northern Lights project within the specified timeframe. These project acceptance criteria were subdivided into the broad categories of seal, formation pressure and sand, including the sand lateral extension and quality as well as the dynamic behaviour of the Johansen Formation as shown in Table 1.

Project acceptance criteria		
Data acquisition	Seal	Drake Fm. 1 claystone presence
		Thickness in line with offset wells
		XLOT results confirm minimum horizontal stress
	Pressure	Hydrostatic (incl uncertainty ± 2 bars) + 3 bar depletion
	Sand	Core description to de-risk depositional environment
	Quality	Kh-product (from well test)
	Extent	Connectivity (well test, depositional model)
	Monitorability	Monitorability Por ~ 15% when Thickness > 5 m (CO_2 20%)

Table 1. Aurora project acceptance criteria defined pre-well.

The data gathered in the 31/5-7 (Eos) exploration well supported the expectations of the Drake Formation to act as a reliable seal to ensure containment of CO_2. The sealing lower part of the Drake Formation (Drake Formation 1) was encountered as a fairly homogenous claystone with a thickness of 75 m. An extended leak-off test (XLOT) was performed that confirmed the sealing potential for future CO_2 injection while additional studies on the core in the Drake Formation will further characterise the cap rock.

Formation pressure data was acquired from Viking, Brent, Dunlin and Statfjord groups. The pressure data confirms previous information from the area with higher depleted formations in the Viking Gp. with minor vertical baffles, and minor depletion in the Brent Group also with vertical baffles to flow. The Dunlin and Statfjord groups have been tested with initial pressure, thus proving no hydraulic communication of the Cook and Johansen formations to the overlying Brent and Viking groups in the well area.

The sand presence and its quality were highly uncertain factors pre-drill due to the under-appraised nature of EL001. The 31/5-7 (Eos) well encountered both Cook and Johansen formations with 57 m and 116 m thickness respectively. Also, the Johansen Formation contains mainly sandstone, with high quality sandstone in the lower and middle part and diminishing quality of the sandstone towards the top of the Johansen Formation. Formation evaluation log data, pressure mobility and core data showed excellent quality of the sandstone units in the Dunlin Group which was confirmed during a production test in the Johansen Formation that is interpreted to a Kh-product (permeability multiplied with reservoir net thickness) of 72 Dm and a radius of investigation of 2200 m – 3200 m without encountering any barriers (Table 2). Given the good quality of the sandstones, the monitorability with 4D seismic is assessed to be feasible and the expectation is that CO_2 can be monitored in layers down to 5-7 m thickness with 20% CO_2 saturation.

Formation	Gross thickness	Net thickness	Net-To-Gross	Porosity	Permeability
	m	m	%	%	mD
Cook Fm. 3	4.1	1.7	41	23	46
Cook Fm. 2	42.8	41.3	96	21	197
Cook Fm. 1	9.8	9.5	97	25	599
Johansen Fm. 4	38.9	37.2	96	23	51
Johansen Fm. 3	11.2	7.7	69	23	76
Johansen Fm. 2	13.2	11.5	87	24	129
Johansen Fm. 1	52.8	49.1	93	21	137

Table 2. Reservoir properties of Cook and Johansen formations including well test results.

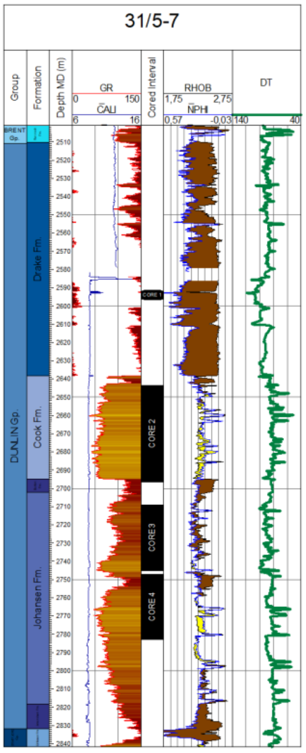

Fig. 8. 31/5-7 (Eos) well composite log in the Dunlin Gp.

Core descriptions and correlations with the Troll area were carried out to update and constrain the depositional systems to be implemented into the static reservoir model. Based on core description, marginal to shallow-marine systems with interplay of fluvial, tidal and wave processes, have been interpreted for the Cook and Johansen fms. The northwards extend of the Johansen Formation in the Aurora area towards Troll is not possible to prove with only one well. Nevertheless, with the assessment of core data, log correlation, assessment of seismic amplitudes and the investigation radius from the well test, the connection of the system from the 31/5-7 (Eos) well towards Troll is given an increased likelihood and confidence.

The results of the exploratory well 31/5-7 (Eos) strongly support Aurora as a suitable CO_2 storage site with a risk profile that is manageable by means of a comprehensive Storage Complex Monitoring plan.

Screening criteria applied to the prospective CO_2 storage sites investigated

Figure 9 shows a qualitative indication of how the analysed types of prospective CO_2 storage sites may generally rank when compared to each other.

This screening tool is developed from the Aurora project acceptance criteria (Table 1), joint with learnings from the assessments done over Smeaheia and Heimdal areas. The tool is based on an ''Evidence Support Logic'' assessment, also known as ''Italian flag'', used to communicate the existence of evidence in favor (green) or evidence against (red) meeting a specific criterion. The ''white space'' is used to indicate uncertainty or data gaps.

It is evident that, before the 31/5-7 (Eos) well was drilled, the Aurora storage site had the largest data gaps and highest level of uncertainties. It also had the highest upside for *Scalability*, lowest *Risk* and *Cost* factors.

With the positive 31/5-7 (Eos) well results, the low side of the *Business Attractiveness* range was lifted, in particular due to the resulting higher level of confidence on the *Storage Resourses & Scalability* factor and a lower *Risk*. However, in relation to future scalability, a relatively high level of uncertainty (white space – Figure 9) still remains, since one (1) data point cannot fully derisk a licensed area of ca. 1400 Km^2.

The 31/5-7 (Eos) well information has provided a relevant basis for Northern Lights Phase 1 development, integrated with (i) understanding of the regional geological setting, (ii) static and dynamic data collected from surrounding areas, and (iii) seismic data covering EL001 license.

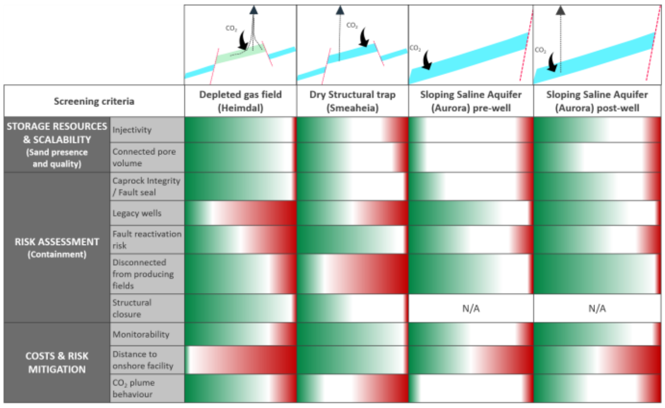

Fig. 9. Screening criteria considered for the three (3) types of assessed prospective CO_2 storage sites: Smeaheia (dry structural traps), Heimdal (depleted gas field), and Aurora (semi-regional sloping saline aquifer).

Figure 10 compares the analysed types of prospective CO_2 storage sites are positioned in terms of *Business Attractiveness*, as defined in the relationship (1). It is also highlighted how relevant *Data availability* is in order to close gaps linked to estimations of attractiveness. Error bars indicate that a detailed assessment of each prospective CO_2 storage site is crucial to determine a *Business Attractiveness* with a higher level of confidence.

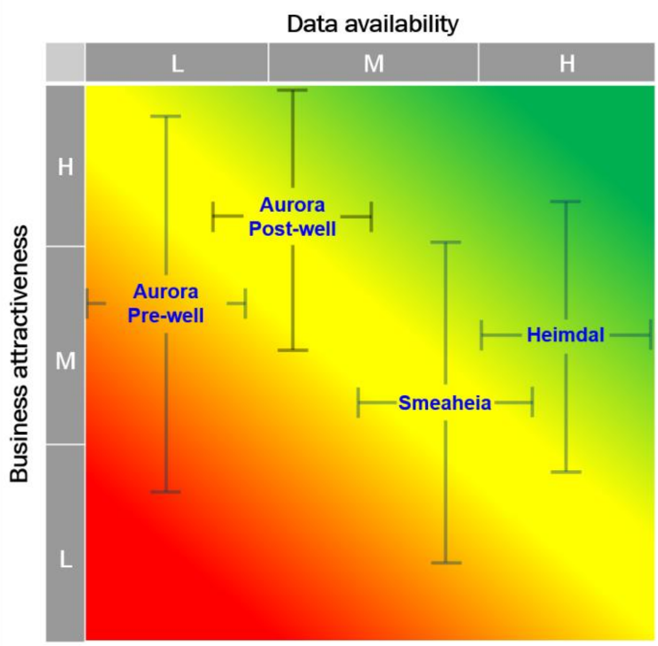

Fig. 10. Business Attractiveness VS. Data availability for the three (3) types of assessed prospective CO_2 storage sites: Smeaheia (dry structural traps), Heimdal (depleted gas field), and Aurora (semi-regional sloping saline aquifer).

Figure 9 and Figure 10 are examples of screening tools that can be incorporated into the prospectivity ranking process of different types of CO_2 storage sites.

Conclusions

An analysis of CO_2 storage prospectivity for the Northern Lights project has been presented. Three types of prospective CO_2 storage sites have been discussed in terms of their main strengths and weaknesses.

Considerations have been presented regarding the need of data and investments to explore and appraise, in order to address uncertainties associated to the 3 subsurface core activities of any CO_2 storage assessment: *Storage Resources & Scalability* estimation, *Risk assessment* and *Costs & Risk Mitigation*.

The need to optimize *Storage Resources & Scalability* with *Cost*, but also with the lowest *Risk* factor, drives workflows for an efficient screening and ranking of prospective CO_2 storage sites. Different screening criteria closely linked to the *Business Attractiveness* of the prospective CO_2 storage sites have been proposed.

The analysis of the Smeaheia storage site, and the subsequent parallel analysis of Heimdal (depleted gas field) and Aurora (semi-regional sloping aquifer), demonstrated that an early definition of the *Risk* factor is key input for estimating the *Business Attractiveness* of a prospective CO_2 storage site.

The relationship of *Business Attractiveness* against *Data availability* is also proposed as a tool to highlight uncertainties, risks and opportunities when screening and ranking CO_2 prospective storage sites.

Based on the 31/5-7 (Eos) well results, Aurora is the most attractive CO_2 storage site for the Northern Lights project with the most balanced *Business Attractiveness* for the Northern Lights project, in particular due the resulting higher *Storage Resources & Scalability* factor, but also a higher level of confidence, and a lower overall residual *Risk*.

References

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N.P., and Mathiassen, O.M., 2007. CO_2 storage capacity estimation: methodology and gaps. *International Journal of Greenhouse Gas Control*, **1**, 430-443.

Bourne, S., Crouch, S., and Smith, M., 2014. A risk-based framework for measurement, monitoring and verification of the Quest CCS Project, Alberta, Canada. *International Journal of Greenhouse Gas Control*, 26, 109-126.

Dalland, A., Worsley, D. and Ofstad, K., 1988. A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *NPD Bulletin*, **4**, 65 pp.

Gassnova, 2013. Geological storage of CO_2 from Mongstad. Interim report Johansen Formation.

Gassnova, 2013. Geologisk CO_2 - Lager Johansen-formasjonen, *GAP analyse iht. Statoils CVP DG2 process, Dok. nr. 13/073-17*.

Halland, E., Gjeldvik, I.T., Tjelta Johansen, W., Magnus, C., Meling, I.M., Pedersen, S., Riis, F., Solbakk T., and Tappel I., 2011. CO_2 Storage Atlas, Norwegian North Sea.

IEAGHG, 2009. A review of the international state of the art in risk assessment guidelines and proposed terminology for use in CO2 geological storage. *IEA Greenhouse Gas R&D Programme*, Report 2009-TR7.

Lauritsen, H.T., Kassold, S., Furre, A-K., and Meneguolo, R., 2018. Assessing potential influence of nearby hydrocarbon production on CO_2 storage at Smeaheia. *Abstract n. 58, EAGE Fifth CO_2 Geological Storage Workshop Latest advances and the way forward.* 21st-23rd November 2018 Utrecht, The Netherlands.

Pawar, R. J., Bromhal, G. S., Carey, J. W., Foxall, W., Korre, A., Ringrose, P. S., and White, J. A., 2015. Recent advances in risk assessment and risk management of geologic CO_2 storage. *International Journal of Greenhouse Gas Control*, **40**, 292-311.

Ringrose, P., 2020. How to Store CO_2 Underground: Insights from early-mover CCS Projects. ISBN 978-3-030-33113-9.

Sundal, A., Nystuen, J. P., Dypvik, H., Miri, R. and Aasgaard, P., 2013. Effects of geological heterogeneity on CO_2 distribution and migration - A case study from the Johansen Formation, Norway. *Energy Procedia*, **37**, 5046-5054.

Sundal, A., Nystuen, J. P., Rørvik, K.-L., Dypvik, H., and Aagaard, P., 2016. The Lower Jurassic Johansen Formation, northern North Sea - Depositional model and reservoir characterization for CO_2 storage. *Marine and Petroleum Geology*, **7**, 1376-1401.

Thibeau, S, Bachu, S., Birkholzer, J., Holloway, S., Neele, F. and Zhou, Q., 2014. Using Pressure and Volumetric Approaches to Estimate CO2 Storage Capacity in Deep Saline Aquifers. *Energy Procedia*, **63**, 5294-5304.

Tucker, O., 2018. Carbon Capture and Storage. ISBN 978-0-7503-1581-4.

Tucker, O., Holleya M., Metcalfeb, R. and Hurstc, S., 2013. Containment risk management for CO_2 storage in a depleted gas field, UK North Sea. *Energy Procedia*, **37**, 4804 – 4817.

Vebenstad K., Vazquez Anzola D. A., Lidstone A., and Zweigel P., 2021. Containment risk assessment of the Northern Lights Aurora CO2 storage site. *15th Greenhouse Gas Control Technologies Conference*. Abu Dhabi 15-18 March 2021 (GHGT-15).

Vollset, J. and Doré, A.G., 1984. A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea. *NPD Bulletin*, 3, 53 pp.

Wu, L., Thorsen, R., Ringrose, P., Ottesen, S., and Hartvedt, K., 2019. Significance of Fault Seal in Assessing CO_2 Storage Capacity and Leakage Risks-An Example from Offshore Norway. *In Fifth International Conference on Fault and Top Seals (Vol. 2019, No. 1, pp. 1-5)*. European Association of Geoscientists & Engineers.

Zweigel, P., Svendsen, T., Talukdar, S., Gemmer, L., Furre, A.K., Bussat, S., Nazarian, B., and Terjesen, H., 2018. The Heimdal Field (North Sea) – A Potential Site for CO_2 Storage in a Depleted Gas Field. *14th Greenhouse Gas Control Technologies Conference.* Melbourne 21-26 October 2018 (GHGT-14).

Figure captions

Fig. 1. Northern Lights full chain schematic.

Fig. 2. Northern Lights portfolio pre-sanction. Location of the assessed potential storage sites in the Northern North Sea, west coast of Norway.

Fig. 3. The three (3) assessed prospective CO_2 storage sites, including a structural closure (Smeaheia), a depleted gas field (Heimdal), and a semi-regional sloping aquifer (Aurora).

Fig. 4. Stratigraphic column highlighting the potential storage reservoir units and seal systems for the prospective CO_2 storage sites investigated.

Fig. 5. CO_2 Storage screening and maturation. The 3 Core Activities for CO_2 storage assessments.

Fig. 6. Regional map of the Horda Platform, offshore Norway, with Aurora and Smeaheia prospective CO2 storage sites in the vicinity of the Troll field. Main fault zones and most important pressure communication links (orange arrows) are shown. Fault traces are mapped at top Sognefjord Formation. From Wu *et al*. (2019).

Fig. 7. Map of the Heimdal gas field indicating its 12 development wells and nearby exploration wells. From Zweigel *et al.* (2018).

Table 1. Aurora project acceptance criteria defined pre-well.

Table 2. Reservoir properties of Cook and Johansen formations including well test results.

Fig. 8. 31/5-7 (Eos) well composite log in the Dunlin Gp.

Fig. 9. Screening criteria considered for the three (3) types of assessed prospective CO_2 storage sites: Smeaheia (dry structural traps), Heimdal (depleted gas field), and Aurora (semi-regional sloping saline aquifer).

Fig. 10. Business Attractiveness VS. Data availability for the three (3) types of assessed prospective CO_2 storage sites: Smeaheia (dry structural traps), Heimdal (depleted gas field), and Aurora (semi-regional sloping saline aquifer).