Annual Experience Report 2025

Northern Lights Joint Venture

Contents

1. Introduction

As required in the State Support Agreement, throughout the Support Period, the Recipient shall prepare an annual experience report. During the Establishment Period, the experience report shall include learning points related to technical solutions and experiences from the project implementation phase, project management, environmental impact, HSE and business models. The Recipient shall also assess potential improvements. As the establishment period covers most of 2025 (until ultimo October 2025), most of 2025 falls under the Establishment period according to the State Support Agreement.

Section 2 provides key experiences gained by the Northern Lights Joint Venture in 2025. This year represented a significant milestone, marked by the commencement of operations involving CO_2 transport vessels and the CO_2 receiving facility, as well as the realization of the full Longship value chain. Certain insights presented in this section may also be incorporated into the Northern Lights Joint Venture Annual Report as part of lessons learned.

2. Technical solutions and experiences

i. Project implementation phase

CO_2 ships

Description

The dedicated and first-of-its-kind CO_2 ships, Northern Pioneer and Northern Pathfinder, arrived in 2025 after successful delivery (in 2024 for Northern Pioneer and 2025 for Northern Pathfinder). These ships are the world's first large-scale, purpose-built liquefied CO_2 carriers, forming an integral part of the Northern Lights value chain. Both vessels have entered operation and have been supporting ongoing activities throughout 2025.

The third ship, Northern Phoenix, which was delivered December 2025, and will arrive in Norway in 2026. The three first vessels are part of the Northern Lights phase 1. A fourth identical sister ship has also been ordered and will be delivered in 2026. This fourth vessel is part of Northern Lights phase 2 and is owned and operated by the German shipowner Bernhard Schulte.

Lessons learned

Using the first vessels (phase 1) as standardised templates has enabled a more seamless, predictable, and cost-efficient process for the construction of future ships of both phase 1, phase 2 and further industry-wide scaling. It additionally established a critical operational benchmark, which had not previously been available due to the vessel's status as the first purpose-built unit for CO_2 transport within the carbon capture and storage (CCS) value chain. Insights gained from the commissioning and operation of the first two vessels enabled the third vessel to be delivered to a higher technical and operational standard. A wide range of enhancements were identified and incorporated into the third vessel, spanning both process related and procedural domains. Several of these improvements involved hardware modifications designed to support a higher level of detail in system validation and to facilitate more robust commissioning of key vessel systems and machinery critical to CO_2 transport within the CCS value chain.

Key technical improvements and operational benefits on vessel three include:

- **Main Engine and LNG Fuel Gas Supply System (FGSS):** Experience gained from the first two vessels highlighted several challenges during the testing and commissioning of the LNG Fuel Gas Supply System, particularly regarding the depth of testing procedures, acceptance criteria, and the capability of the original equipment manufacturing (OEM's) locally approved contractor. These issues contributed to post-delivery engine performance problems on vessels one and two, necessitating additional troubleshooting and technical interventions. For vessel three, a more robust approach was implemented. Testing standards were clarified, information exchange with the OEM was improved, and enhanced validation protocols were introduced. This collaborative effort resulted in important pre-delivery upgrades, including revised engine software and improved gas-injection nozzles. Consequently, vessel three demonstrated markedly higher engine reliability and performance from its maiden voyage. Operational learnings from vessels one and two improved the reliability of the engine's LNG-burning performance. In addition, enhanced understanding and testing of the Power Management System (PMS) and its associated software on vessels three and four (phase 2) helped identify measures to prevent potential blackout scenarios.

- **CO_2 Cargo Trials and Process Optimisation:** Vessels one and two conducted the first operational trials involving liquefied CO_2, establishing the initial foundation for cargo-handling parameters such as flow rates, loading and discharge durations, and the behaviour of the cargo under operational conditions. These were pioneering efforts within the CCS maritime sector, and they generated extensive technical and procedural learning. All findings from these initial trials were systematically documented and transferred to vessel three. As a result, the third vessel entered its trials with a mature set of validated procedures, allowing for more efficient operations and improved predictability.
- **Shore Power Capability:** Post-delivery experience with vessels one and two revealed issues with shore-power integration, including instability and insufficient capacity during cargo-handling operations. A detailed investigation involving multiple OEMs identified the underlying technical causes and defined corrective actions. Based on these findings, vessel three was built with design modifications enabling it to accept higher-capacity shore power reliably, particularly during discharge operations. The modifications have enabled the vessel to discharge at full capacity, improving

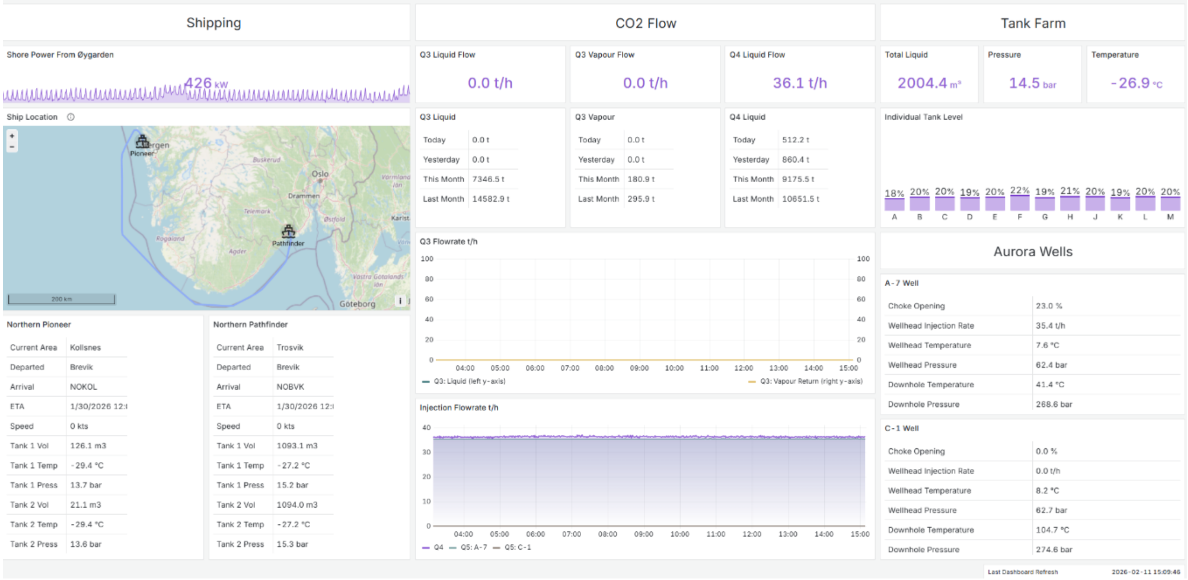
scheduling efficiency and offering potential fuel savings by reducing reliance on the vessel’s generators.

In addition to the technical improvements and operational benefits identified from vessels one and two, vessel three demonstrated a reduction in required working hours. Vessel three recorded 912,909 working hours, compared with an average of 1,061,254 working hours for vessels one and two, representing a reduction of approximately 150,000 working hours.

Logistics of the CCS value chain

Description

Efficient logistics across the CCS value chain require full understanding and control of the CO_2 molecule from the point of capture to storage. Successful operations depend on well-functioning communication lines between all parties in the value chain.



Shipping

Shore Power From Øygarden: 426 kW

Northern Pioneer

Current Area	Kollsnes
Departed	Brevik
Arrival	NOKOL
ETA	1/30/2026 12:
Speed	0 kts
Tank 1 Vol	126.1 m3
Tank 1 Temp	-29.4 °C
Tank 1 Press	13.7 bar
Tank 2 Vol	21.1 m3
Tank 2 Temp	-29.4 °C
Tank 2 Press	13.6 bar

Northern Pathfinder

Current Area	Trosvik
Departed	Brevik
Arrival	NOBVK
ETA	1/30/2026 12:
Speed	0 kts
Tank 1 Vol	1093.1 m3
Tank 1 Temp	-27.2 °C
Tank 1 Press	15.2 bar
Tank 2 Vol	1094.0 m3
Tank 2 Temp	-27.2 °C
Tank 2 Press	15.3 bar

CO2 Flow

Q3 Liquid Flow: 0.0 t/h

Q3 Vapour Flow: 0.0 t/h

Q4 Liquid Flow: 36.1 t/h

Q3 Liquid

Today	0.0 t
Yesterday	0.0 t
This Month	7346.5 t
Last Month	14582.9 t

Q3 Vapour

Today	0.0 t
Yesterday	0.0 t
This Month	180.9 t
Last Month	295.9 t

Q4 Liquid

Today	512.2 t
Yesterday	860.4 t
This Month	9175.5 t
Last Month	10651.5 t

Tank Farm

Total Liquid: 2004.4 m³

Pressure: 14.5 bar

Temperature: -26.9 °C

Aurora Wells

A-7 Well

Choke Opening	23.0 %
Wellhead Injection Rate	35.4 t/h
Wellhead Temperature	7.6 °C
Wellhead Pressure	62.4 bar
Downhole Temperature	41.4 °C
Downhole Pressure	268.6 bar

C-1 Well

Choke Opening	0.0 %
Wellhead Injection Rate	0.0 t/h
Wellhead Temperature	8.2 °C
Wellhead Pressure	62.7 bar
Downhole Temperature	104.7 °C
Downhole Pressure	274.6 bar

Last Dashboard Refresh 2026-02-11 15:09:46

Snip of Northern Light's dashboard showing real time date on transport, storage, in addition to data from injections and wells

Lessons learned

During phase 1, the ship-based logistics chain functioned largely as planned, but maintaining continuous injection required more coordination than initially anticipated. Variability in CO_2 production affected loading schedules and shipping plans, and because injection operations rely on stable supply, frequent adjustments were necessary. At times, injection had to be temporarily paused. Managing this dynamic required close, daily coordination between capture, transport, and storage operations, highlighting the importance of developing robust logistic systems for collecting and transporting CO_2 to ensure an uninterrupted supply to the facility and move toward fully digital data exchange between capture sites, ships, terminals and subsurface units, enabling real-time monitoring.

An important lesson learned is the need to understand customer requirements early so that efficient logistics solutions can be aligned with operational readiness. And further, the need to align ways of working across organizations with different industrial backgrounds. The transport and storage team primarily has experience from shipping and oil & gas, where strict scheduling, marine logistics discipline, and continuous operations are standard practice. The capture teams largely come from the cement industry, where production variability is managed differently. Early in phase 1, it took time to establish a shared understanding of each other's operational constraints, forecasting practices, and decision-making processes. As coordination meetings became more frequent and interface definitions were clarified, collaboration gradually became more structured and predictable. Early involvement of all parties reduces uncertainty and supports smoother planning across the value chain. Regular coordination between capture, transport, terminals, and subsurface operations helps prevent delays and ensures more efficient execution.

For the first cargoes, CO_2 specification verification was based on manual sampling and laboratory analysis. Due to frequent schedule changes, coordinating sampling, analysis and loading windows proved demanding. As operations progressed, procedures were streamlined, communication routines formalized and planning moved toward rolling forecasts rather than fixed schedules. A key lesson learned and improvement going forward is to conduct sampling at the outset for all customers to ensure meter integrity and proper calibration.

The availability of two vessels provided essential flexibility, and as crews gained experience with first-of-a-kind CO_2 carriers, cargo handling routines became more efficient, Together, these improvements strengthened the robustness of the logistics chain and reduced the operational impact of ongoing production variability.

Pipeline cleanliness and high flow flushing

Description

Ensuring sufficient pipeline cleanliness prior to handover to operations is critical for safe and reliable CO_2 transport. For Northern Lights phase 1, the pipeline was cleaned through a combination of pre-installation cleaning of pipe joints and stalks, and post-installation cleaning using pigging and flushing. Due to delayed completion of the landfall tunnel, pipeline installation was split over two seasons, with offshore and nearshore sections installed and cleaned separately. Based on experience from similar carbon steel pipelines without internal coating, a more conservative cleaning approach was selected. This included an extended pigging programme and the use of filtered seawater to suspend and remove particles.

Due to stringent cleanliness criteria implemented late in the project, it was necessary to perform additional cleaning over and above what initial planed. This additional high-flow flushing was performed to remove any remaining particles that could be mobilised during higher CO_2 injection rates planned for phase 2. Calculations performed by Flow Assurance, indicate that particles up to 2 mm in size will be removed during the high flow flushing operation

A high flow flushing operation was carried out with filtered seawater as follow:

- The pipeline was flushed with flowrate > 750 m3/hr for 79,2 hrs versus planned 36 hrs. The flushing was maintained for a prolonged duration due to nature of subsea discharge.
- Once it was realized that the brownish discharge was due to instantaneous corrosion in the pipeline, the flushing was stopped and injection of chemically treated seawater commenced for preservation of the pipeline until dewatering operation.
- After 1.38 times line fill volume had been discharged after chemical injection had started, the subsea discharge was clear.

Main equipment installed at Energiparken.

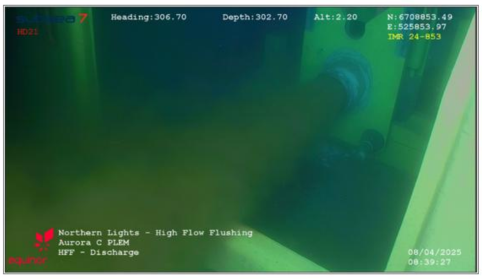


Photo taken as chemically treated water starts discharging

Photo before pumping was stopped

Lessons learned

An important lesson learned relates to optimizing flushing and cleanliness strategies for CO_2 pipelines. Operational experience indicated that the originally planned 36-hour flushing program would likely have been sufficient, as the brownish subsea discharge observed was caused by instantaneous corrosion during the operation rather than by remaining debris, which is representing potential for reduced operational duration and cost. High-flow flushing proved effective in removing residual particles prior to increasing injection rates, supporting the value of a conservative pigging and flushing approach, particularly for carbon-steel pipelines without internal coating. For future CO_2 infrastructure, establishing clear cleanliness requirements early in the project and progressing the qualification of internal coatings for carbon-steel CO_2 pipelines will further reduce uncertainty and strengthen operational reliability.

First Fill

Descriptions

The purpose for first-fill was to bring the onshore terminal into a state in which liquid CO_2 can safely be introduced and stored in the facility. The activity focused on the Northern Lights onshore terminal in Øygarden from the loading arms to the Emergency Shot Down (ESD) valve before the export pipeline. Once the facility was mechanically completed and ready to receive some type of gas the following steps was performed to reach the point where liquid CO_2 could be introduced into the facility:

1. Dry the facility with air.
2. Leak test the facility with nitrogen up to 7 barg. Due to delays there was an opportunity for an additional leak test performed up to 16 barg.
3. Displace the present medium with CO_2 by means of purging.
    - First sweep purging avoiding pressure increase to limit possible residual liquid dropout.
    - Pressure swings to ensure the dead ends are also purged.
4. Ensure facility is pressurized to minimum pressure to avoid dry ice formation.
5. Introduce liquid CO_2 for further cooldown of the facility. Liquid boil off will further purge the facility.

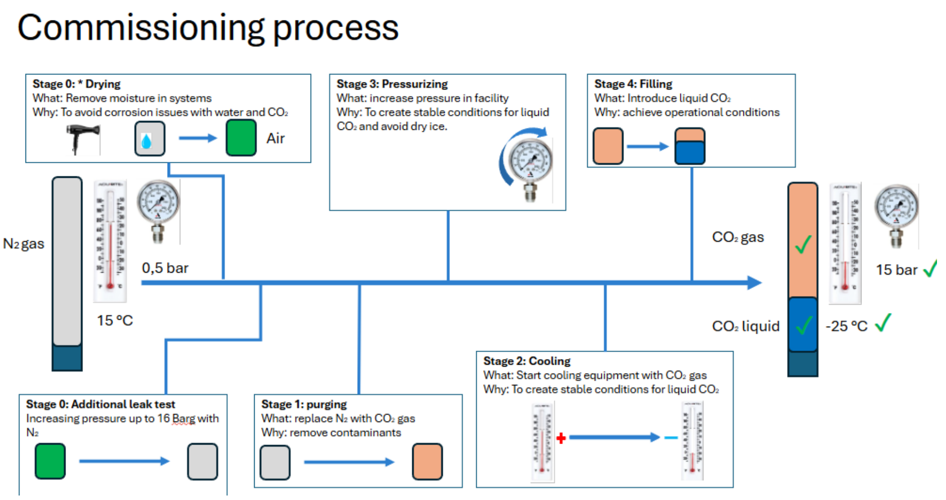
The initial plan was to perform this activity with CO_2 volume from Heidelberg, but due to delays at Heidelberg an alternative plan was made where CO_2 was purchased from Nipon Gases to be used for first-fill. Nippon Gases had the capacity to supply liquid CO_2 by truck and ship from within Norway hereby avoiding potential cross border CO_2 transport limitations. The decision was made to start the activities with truck deliveries since these offered more flexibility and would limit the cost of having a ship moored at the jetty for several weeks. The first-all activities included the following:

- All 12 storage tanks and piping were purging through with CO_2.
- The entire facility was pressurised to a minimum of 7 barg to mitigate the risk of dry ice formation.
- Additional pressure cycles (purging) on only 3 tanks which would be enough to receive one ship cargo from Nippon Gases (roughly 1750 t of liquid CO_2).

- The decision to continue with pressure cycles to further purge the three tanks was mainly driven by the necessity to provide clean vapor return to Nippon Gases which would not have been achieved by, only sweep purging the tanks.
- The CO_2 volumes delivered by ship was stored in the 3 tanks as a local CO_2 source to continue pressure cycling the other 9 storage tanks and finish the conditioning of the facility.

An evaluation was performed concerning the risk of damage to the facility or reservoir and how to mitigate these and it was decided to install 1 micron filters in two places in the facility to protect the facility and reservoir from particles. Due to limited time and criticality to have the filters installed before dewatering of the pipeline a separate temporary filter skid was installed also with 1 micron mesh.

The liquid CO2 volume from all 12 tanks was pumped through the temporary filter before these were inspected. Only discolouration was observed and no solids. The filter cartridges were exchanged prior to start-up of the dewatering operations.


Commissioning process

Stage 0: * Drying
What: Remove moisture in systems
Why: To avoid corrosion issues with water and CO_2

Stage 3: Pressurizing
What: increase pressure in facility
Why: To create stable conditions for liquid CO_2 and avoid dry ice.

Stage 4: Filling
What: Introduce liquid CO_2
Why: achieve operational conditions

Stage 0: Additional leak test
Increasing pressure up to 16 Barg with N_2

Stage 1: purging
What: replace N_2 with CO_2 gas
Why: remove contaminants

Stage 2: Cooling
What: Start cooling equipment with CO_2 gas
Why: To create stable conditions for liquid CO_2

:


Offloading by means of hoses from the Nippon Ships

Unloading CO_2 from Trucks to the facility

Lessons learned

A key lesson learned is the importance of ensuring effective drying of the facility before introducing CO_2, where the use of hot air has shown clear benefits in improving overall drying efficiency. Experience also demonstrated that additional leak testing at higher pressures, such as 16 barg, offered limited added value and should be carefully assessed for future campaigns. There is also an opportunity to evaluate the use of CO_2 vapour directly for leak testing instead of nitrogen, which may provide cost savings. Furthermore, first-fill activities are fully dependent on the timely delivery of liquid CO_2 from the emitter, and any changes can affect the sequence and duration of the work. Establishing contingency plans early therefore helps reduce uncertainty and mitigate potential schedule impacts. It is equally important to clarify at an early stage how CO_2 from alternative sources will be managed to avoid delays and unexpected costs.

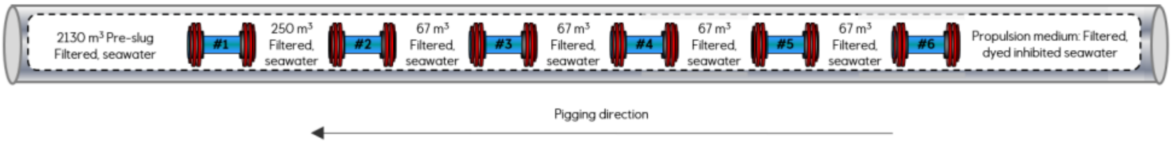
Dewatering

Description

For Northern Lights phase 1, the dewatering of the CO_2 pipeline was a critical activity prior to introducing CO_2 and starting operations. The dewatering operation was designed in accordance with internal requirements and relevant industry standards, ensuring the pipeline was sufficiently dried to prevent corrosion before CO_2 introduction. A conservative pig train design was selected, using an initial nitrogen batch to drain water from pipeline branches, followed by multiple MonoEthyleneGlycol (MEG) slugs to condition the pipeline and achieve the required dryness.

The first slug in the pig train consisted of a batch of nitrogen. This was included to drain water from the pipeline branches (inline T's, PLEM piping and Morgrip annulus). The water was drained out of these elements into the nitrogen batch to avoid contamination of the glycol slugs in the pig train.

The remaining slugs in the pig train each consisted of 50 m3 MEG with a 100 percent purity. Their function was to condition the pipe wall and prepare the pipeline for contact with liquid CO_2.

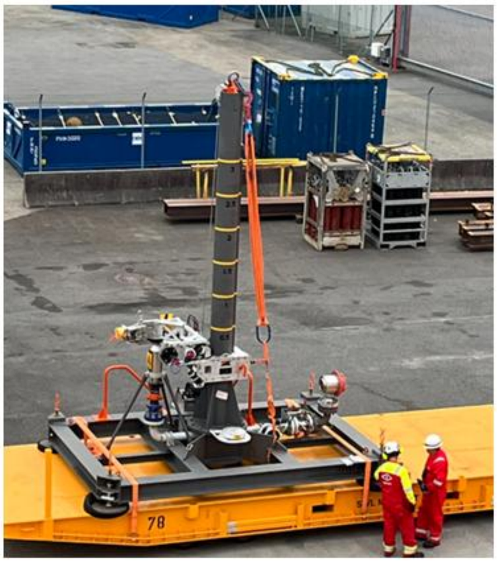


Pig train set-up

The original plan was to propel the dewatering pig train using compressed nitrogen gas. To reduce cost, environmental impact and operational complexity, a project change was approved to use liquid CO_2 as the propulsion medium instead.

Pig Launcher Location

When the final pig in the dewatering train entered the subsea pig receiver, a small amount of CO_2 was released into the sea. This event provided a rare opportunity to gather data from a release involving significant CO_2 flow rates and volumes, far greater than what is usually possible in laboratory tests. SINTEF, in collaboration with oil industry operators, had previously developed a simulation tool for analyzing gas plumes from hydrocarbon releases into the sea, which was later adapted for CO_2. However, the model lacked calibration data from real large-scale CO_2 releases. To address this, data collection was incorporated into the CO_2 release phase following the dewatering and drying operation. To enable proper measurements, the basic discharge setup used for dewatering was replaced with a specially designed, instrumented system. Two offshore CO_2 release tests were performed, each lasting 60 minutes at a flow rate of 120 m^3/h. The collected data will be processed by SINTEF to refine the CO_2 plume simulation model.



CO_2 experiment discharge skid

Lessons learned

A key lesson learned from the dewatering operation is the value of strong coordination between onshore and offshore teams, which enabled the work to be completed ahead of schedule (nine offshore days compared with the eleven planned). A shared Teams channel proved particularly effective for real-time communication and decision-making. When CO_2 injection commenced, it became clear that achieving the planned flowrate of 190 m^3/hr was not feasible due to higher-than-expected restrictions in the subsea check valve, which required greater pressure at elevated flowrates. This resulted in approximately ten additional hours of operation and an achieved flowrate of around 150 m^3/hr. To maintain high flow under these conditions, higher pressure than originally planned had to be applied from Energiparken, leading to a higher pipeline pressure at completion. Flow assurance simulations confirmed that the pipeline could safely remain at 120 barg, compared with the originally planned 70 barg. The operation demonstrated that using CO_2 as the propulsion medium for pigging during dewatering can offer both cost savings and environmental benefits, but also highlighted that CO_2-based dewatering requires thorough planning and careful execution to ensure acceptable risk and timely completion.

Operational start-up

Description

The operational start-up marked the transition from construction to full-scale operation of the Northern Lights value chain. This included commissioning of on- and offshore facilities, first loading and unloading, integration of shipping and terminal systems, and establishing routines for safe and reliable day-to-day operations. As this is the first commercial CO_2 transport and storage system of its kind, close coordination between technical teams, operators and external partners was crucial.

Monitoring from the control room at the Øygarden CO_2 receiving facility to monitor that the CO_2 has been injected into the reservoir.

Lessons learned

An important lesson learned from the operational start-up phase was the value of early testing and cooldown to understand tank behaviour over extended periods without new CO_2 input, including monitoring how temperature and pressure evolved over time. Several modifications were required, such as installing a filter to protect well injectivity and strengthening equipment and wall-thickness monitoring to accommodate changes in CO_2 specification. Early involvement of operations personnel proved highly beneficial, as their familiarity with the facility and understanding of operational risks contributed to safer and more efficient decision-making. The current design is still largely based on traditional oil and gas frameworks and has only been partially adapted to the specific requirements of CO_2 operations; future phases should more fully reflect CO_2-specific operational characteristics. It also became clear that requirements from different authorities need to be more clearly distinguished and integrated into design processes from the outset. Furthermore, the importance of having a robust Monitoring, Reporting and Verification (MRV) framework and digital solution from startup and in place for the first operations was reinforced, ensuring transparency and accuracy in documenting transported and stored CO_2 volumes across customers and CO_2 streams. Lastly, external expectations often assumed full and continuous operations from the first day, with immediate availability of operational learnings. In practice, the transition into operations required a start-up and ramp-up period, particularly for a first-of-its-kind project within a newly established value chain, making active expectation management across stakeholder groups essential.

More details on operational start-up with a focus on the technological aspect was provided in four online sessions on learnings from phase 1 TSP. These presentations have been shared with Gassnova on 16th December 2025.

ii. Environmental impact

CO_2 specifications

Description

Liquid CO_2 has specific properties that require careful handling to ensure safe and reliable carbon transport and storage. To safeguard the Northern Lights value chain, specification for Liquid CO_2 quality was developed to define required purity and acceptable levels of admissible impurities. This specification protects material integrity both for emitters and in pipeline, temporary storage, ships, and offshore facilities, and ensure safe operations.

Without compromising safety or integrity, defining impurity limits in the CO_2 specification involves balancing acceptable levels across different impurity groups, while avoiding unnecessary exclusion of specific industries or capture technologies and limiting additional cost burdens on emitters.

Lessons learned

A key lesson learned is that CO_2 specifications must evolve in step with the maturing CCS industry. As new research, operational insights and industry feedback emerged, it became clear that updates were needed to maintain safety and system integrity. In 2025, additional testing of specific impurities confirmed the need for a further refinement, lowering the allowable limit for one impurity to protect the mechanical integrity of the full value chain. The revised specifications, published in May 2025, reflect this precautionary approach. This experience highlights the importance of strengthening integrated decision-making by incorporating commercial and regulatory considerations alongside technical design decisions. It also underlines the need for companies across the CCS value chain to continue developing and updating their own specifications for future projects as knowledge continues to advance.

iii. HSE

Authority processes

Description

Injection and storage of CO_2 require a formal consent issued by the Ministry of Energy. The application for the consent was submitted in January 2024, following alignment meetings between the Ministry of Energy, Equinor as the Technical Service Provider (TSP), and the Northern Lights Joint Venture to agree on the appropriate format and content of the application. One year after the submission, the Ministry of Energy informed Northern Lights of its intention to transfer responsibility for processing such applications to the Norwegian Offshore Directorate. This intended transfer was cited as the primary reason for requesting a revised application with updated form and content. The transfer of responsibility from the Ministry of Energy to the Norwegian Offshore Directorate was ultimately not implemented.

Lessons learned

A key lesson learned is the importance of maintaining close and continuous engagement with the relevant authorities throughout the permitting process, as this enables a proactive and well-coordinated approach and is a core responsibility of the operator. It is equally important to encourage cooperation across the various authority bodies involved rather than focusing on individual stakeholders or applications in isolation. As CCS activity scales across Europe, it becomes increasingly critical that both national and EU-level authorities draw on the experience from Northern Lights phase 1 to ensure that regulatory processes are workable and feasible for future projects. Establishing regular follow-up routines with the authorities, alongside strengthened cooperation and coordination between responsible bodies, helps support more predictable permitting timelines. Furthermore, there is clear value in authorities considering the consolidation or harmonisation of overlapping regulatory requirements to improve alignment of submission and decision schedules across the full value chain.

iv. Business models

Advancing the business case for CCS

Description

Throughout 2025, Northern Lights made strides in advancing the business case for CCS. The commercial agreement with the Swedish energy provider, Stockholm Exergi, for cross-border transport and storage of up to 900,000 tonnes of biogenic CO_2 annually enabled the investment decision to expand Northern Lights' CO_2 transport and storage services from 1.5 million to more than 5 million tonnes of CO_2 per year, enabling further reduction and removal of European industrial CO_2 emissions. The investment made by the Northern Lights JV owners Equinor, Shell and TotalEnergies are 7.5 billion NOK. This includes the enabling grant of €131 million from the Connecting Europe Facility for Energy (CEF Energy) funding scheme, approved by the European Commission in June 2024.

Lessons learned

A key lesson learned is that the investment decision marked an important step toward building a commercially viable CCS market in Europe and reaffirmed Northern Lights' commitment to providing an effective decarbonisation solution. However, taking a final investment decision remains a complex, multi-stakeholder process in which coordination is a primary bottleneck. Establishing a shared negotiation timeline from the outset with clear milestones leading up to the respective FIDs, proves essential to maintaining alignment and, importantly, identifying potential misalignments early enough to take corrective action. Improved dialogue and closer coordination across the value chain are therefore critical to de-risking future projects, especially where shared infrastructure is involved. The experience demonstrates that the challenge is not only about technical maturity of the projects, but also the ability of all parties to reach decisions at the right time and in a coordinated manner.

Credible carbon accounting

Description

Credible carbon accounting is key to the integrity of the emerging CCS industry. The Monitoring, Reporting and Verification (MRV) framework and digital MRV (dMRV) in Northern Lights are designed to deliver the transparency, traceability and accuracy required by both compliance and voluntary carbon markets. It is essential for such an MRV framework to take into account not only the transported and stored CO_2 volumes, but also the value chain life cycle emissions and how these are allocated to volumes transported and stored over the lifetime of the project. Hence, NLJV's standardized MRV solution had to be developed and operational in time for reception of the first CO_2 volumes from Heidelberg. A robust and transparent MRV is important for the entire CCS value chain to document the storage of captured co2. By issuing CO_2 storage certificates based on the MRV system, Northern Lights provides industrial emitters with verifiable, auditable proof that their CO_2 has been safely stored in the reservoir. This proof point is essential in a growing market for decarbonised products and services, where documented climate impact is becoming a competitive requirement. Northern Lights has now issued the first-ever storage certificates, confirming that CO_2 captured at Heidelberg Materials' cement plant in Brevik has been transported and securely stored in the reservoir. This milestone demonstrates that the full CCS value chain - from capture to storage - is not only operational but also measurable, transparent, and trustworthy.

Lessons learned

A key lesson learned is the importance of having a robust MRV framework and digital solution in place from the start of operations to ensure transparency and accuracy of the co2 streams in the value chain. The scope and complexity of an MRV system capable of documenting transported and stored CO_2 volumes, as well as associated emissions across both transport and storage sections, is significant, particularly given the requirements of compliance and voluntary carbon markets. Early recognition of both the complexity and the strategic importance of establishing the MRV framework proved essential, especially in a market environment where compliance expectations and voluntary market dynamics have been strong drivers during the establishment phase of CCS.

3. Improvements relevant for research and development

Northern Lights currently focussed most of its collaboration on geophysical and monitoring activities. These activities include:

- Safe-C: harmonization of passive seismic databases across national boundaries.
- Inversion of 4D signal for calculation of stored CO_2 volumes: Amplitude proportional to saturation, but challenge related to different storage mechanisms simultaneously, with dissolution as the most important.
- DAS for active seismic monitoring (4D VSP).
- Strain modelling inversion in DAS (multi-physics DAS). Currently, no correlation between strain and signal established.
- Sparse geophone array (patches of clustered geophones) for cost-effective monitoring.
- Decimation of seismic signal (less points, faster acquisition) to provide more information after first seismic repeat and/or synthetic modelling.

Further areas of interest that could be developed in the future to support the emerging CCS market are:

- Effects of intermittent injection on the injection system and reservoir.
- CO_2 composition measurement methods.
- Impact of CO_2 composition on material choices and corrosion management.
- Management and optimisation of logistics, including hubs.
- Application of direct injection technology and its impact on the CCS offer to customers.
- Data management and data reduction to run effective CO_2 tracking systems from origin to storage.
- Scaling of CCS chain for smaller emitters and methods of CO_2 transportation.
- Understanding future development of the EU ETS system, CBAM, CDRs and their impact on CCS industry.

4. Summary

A short summary highlighting the most critical learning points in 2025 across the full value chain:

- In 2025, Northern Lights gained critical experience demonstrating that coordinated decision-making across the full CCS value chain is essential for safe, reliable and predictable operations.
- Technically, first-of-a-kind CO_2 ships, pipeline systems and onshore facilities performed as intended, but operational readiness benefitted significantly from early testing, strong coordination between onshore and offshore teams, and iterative improvements to CO_2 specifications and pipeline cleanliness strategies.
- Operational experience underscored the need for stable logistics, real-time communication across capture, shipping, terminal and subsurface units, and alignment of working practices between industries with different operational cultures.
- From a project-management perspective, early integration of operations personnel, clear interface definitions and coordinated milestone planning proved decisive in reducing handover risk and supporting a smoother transition into operations.
- In the HSE and regulatory domain, consistent engagement with authorities and better coordination across regulatory bodies were essential to navigate permitting processes and ensure predictable timelines.
- Finally, business-model experience highlighted that future CCS deployment will depend on coordinated FID timelines and stronger alignment across stakeholders, while the establishment of a robust Monitoring, Reporting and Verification (MRV) framework from day one is foundational for credible carbon accounting and market trust.

Together, these lessons show that the bottleneck in 2025 is not technology, but rather coordination across timelines, stakeholders, and regulatory frameworks to unlock investment and enable CCS at scale.