CO_2 measurement in Longship

Introduction

Carbon Capture and Storage (CCS) is a crucial technology for reducing greenhouse gas emissions and achieving climate targets. The Longship project represents Norway's comprehensive commitment to CCS and includes, among others, Northern Lights and Brevik CCS, which will become operational in 2025, as well as Oslo CCS, with planned operations starting in 2029.

Longship aims to demonstrate the technological and economic viability of CO_2 management from industrial point sources, establish infrastructure for CO_2 transport and storage, facilitate international knowledge transfer, and position Norway as a global leader in CCS.

Measurement is essential to ensure safe and efficient handling of CO_2 throughout the entire value chain—from capture to storage. Measurement stations are required at every stage—capture, transport, and storage—to enable regulatory reporting, ownership transfer, accurate quantity allocation, and safe process control. This ensures accurate tracking of the amount of CO_2 captured and stored and guarantees regulatory compliance.

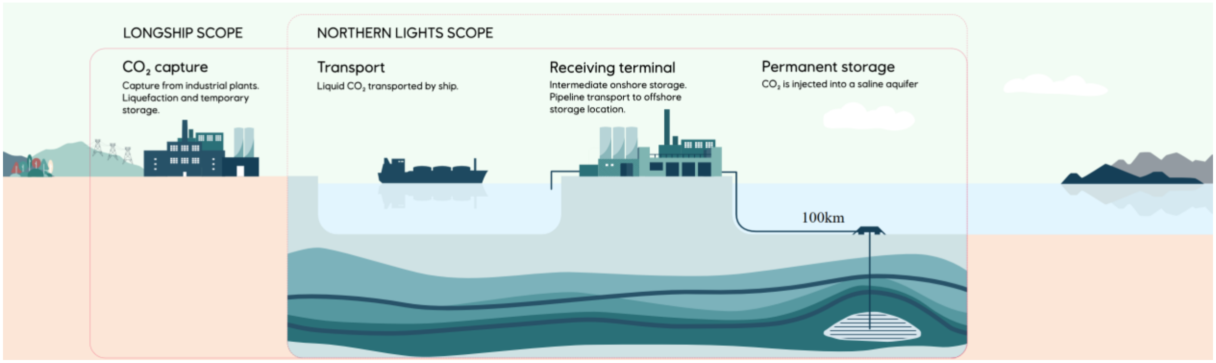

Figure 1: Longship value chain. Ref: The Northern Lights project - Equinor

Roles and regulatory requirements

Northern Lights is responsible for CO_2 measurement and reporting from the point of custody transfer at the capture plants to permanent storage. The capture actors are responsible for measurements prior to this point.
The authorities impose strict documentation requirements—reporting must include the amount of CO_2 actually stored in the reservoir, the composition and quality of this amount, and whether there have been any emissions to the external environment.

Each delivery must be documented and verified. Specification deviations can result in the rejection of LCO_2 shipments at loading.

Longship value chain

The Longship value chain comprises three main phases—capture, transport, and permanent storage:
Capture:
Flue gas contains a mixture of various substances, including water vapor and CO_2, as well as impurities like nitrogen oxides (NO_x), sulphur oxides (SO_x), and hydrogen sulphide (H_2S). The capture

process separates CO_2 from the rest of the flue gas, compresses and cools it into liquid form to meet the downstream requirements for the transport and storage.

Transport: The CO_2 is transported using specially designed ships, such as the Northern Pathfinder and Northern Pioneer. These ships carry the chilled and compressed CO_2 to the Northern Lights reception terminal at Øygarden. From the terminal, the CO_2 is transported via an approximately 100 km long underground pipeline to the injection well. The combination of pipeline and ship transportation creates a flexible transport system for safe CO_2 delivery to the storage site.

Permanent storage: In the storage phase, CO_2 is injected into deep geological formations beneath the seabed southwest of Øygarden on the Norwegian continental shelf. This area has been carefully selected due to its favourable reservoir properties for permanent CO_2 storage. Storage is closely monitored to ensure the CO_2 remains safely sealed underground.

CO_2-specification

To enable safe and efficient CO_2 transport and storage in the Longship project, the CO_2 must meet a defined specification regarding chemical composition and physical properties, see Figure 2. The CO_2 specification requires a purity of at least 99.97%, accounting for the sum of all allowed impurities. Key contaminant limits include:

- Water (H_2O): strictly limited to prevent corrosion and hydrate formation
- Oxygen (O_2: restricted to avoid unwanted chemical reactions
- Hydrogen sulphide (H_2S): limited for safety and corrosion control

Quality is continuously monitored, primarily through online gas analysers for H_2O and O_2. While H_2S is part of the specification, online analysis of H_2S is not a requirement.

In addition, the CO_2 must remain in liquid phase throughout the transport chain, which requires maintaining a minimum pressure of 15 barg and a temperature around –26°C. The CO_2 density under these conditions is essential for accurate mass balance calculations.

This specification acts as a common reference across the value chain, ensuring that the captured, transported, and stored CO_2 complies with both technical standards and regulatory requirements.

Component	Concentration, ppm (mol)
Water (H_2O)	≤ 30
Oxygen (O_2)	≤ 10
Sulphur oxides (SOx)	≤ 10
Nitric oxide/Nitrogen dioxide (NOx)	≤ 10
Hydrogen sulphide (H_2S)	≤ 9
Carbon monoxide (CO)	≤ 100
Amine	≤ 10
Ammonia (NH_3)	≤ 10
Hydrogen (H_2)	≤ 50
Formaldehyde	≤ 20
Acetaldehyde	≤ 20
Mercury (Hg)	≤ 0.03
Cadmium (Cd), Thallium, (Tl)	Sum ≤ 0.03

Figure 2: Current specification for CO_2 in Longship.

Longship critical metering points

To ensure traceability, settlement, and documentation across the entire Longship value chain, critical metering points have been established from capture to permanent storage, see Figure 3.

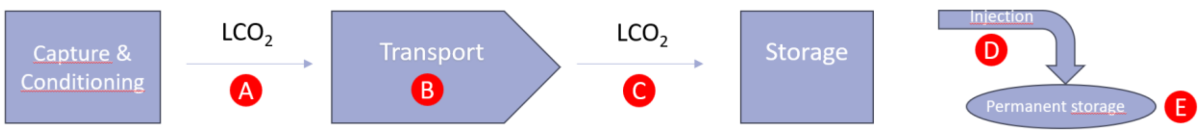

Figure 3: Critical metering points in the Longship value chain.

Metering point A: loading from capture plant to ship

During loading of liquid CO_2 loading from the capture facility to the ship, ownership is formally transferred from the capture operator to the storage operator. However, the online transfer measurement at this point is considered a process measurement — it is not classified as a fiscal measurement, meaning it is not highly accurate nor critical for custody transfer. If the measurement system is unavailable or fails, loading can still proceed.
CO_2 quality must be confirmed prior to loading. If the specification is not met, the ship's captain may reject the cargo. Quality is monitored using online gas analysers for H_2O and O_2; while H_2S is part of the quality specification, its online monitoring is not required.

Physical parameters such as quantity, pressure, temperature, and density are recorded using field instruments to support operational monitoring and ship loading documentation.

Metering point B: CO2 ship

During loading, the CO_2 quantity filled into the tanks must be measured accurately for documentation and regulatory reporting.
The ships are equipped with radar-based tank gauges and sensors that monitor pressure and temperature in each tank. All data is processed in a Custody Transfer Management System (CTMS), which ensures traceable and automated documentation of transfers and transport conditions.

Metering point C: unloading at Øygarden terminal

At unloading, the same measurements as at loading are repeated to verify the delivered amount. The CTMS on the ship is used to verify the volume received at Øygarden and acts as a fiscal meter. Any deviation is reported and handled under the Standard Shipping Agreement (SSA), which allows for a limited acceptable loss during transport.

The CO_2 quality is re-verified using online analysers, which continuously monitor a total of 26 different impurities. Once the liquid CO_2 is unloaded, it is mixed into shared storage tanks, making it impossible to trace individual batches. Consequently, the quantity loaded at the capture plant serves as the reference for subsidy allocation and quota accounting.

Metering point D: injection from terminal to the reservoir

At the onshore terminal, after the injection pump, CO_2 is measured as it is transferred toward the offshore reservoir. This point serves as the battery limit, beyond which the CO_2 is considered permanently stored.
Venturi meters are used to perform continuous measurement of the injected CO_2. These measurements are essential for regulatory reporting, mass balance calculations, and verification of permanent storage.

Metering point E: monitoring of the permanent storage

After injection, the permanent storage site is continuously monitored to ensure that CO_2 remains safely stored and does not leak. Various methods are used to detect movement and changes in and around the reservoir.

Measurement instrumentation

A wide range of instruments is used to suit the varying physical conditions of CO_2, whether in gas or liquid form. Both field (online) and lab (offline) instruments are used.
Online sensors and flow meters provide continuous operational monitoring and deliver digital readings directly to the control system. Lab-based measurements offer higher precision for quality control and calibration.
The most critical instruments measure quantity (see Figure 4), chemical composition, and physical properties like pressure, temperature and density.

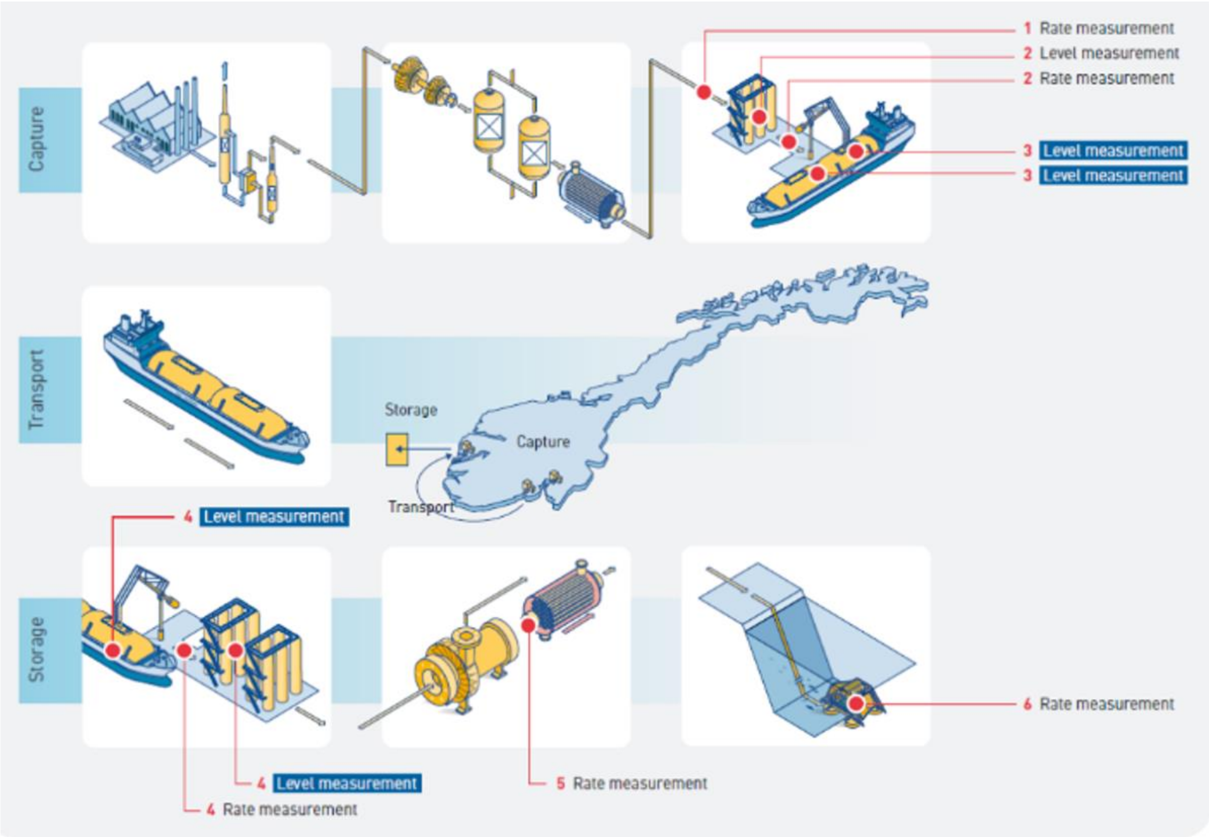

Figure 4: Overview over critical instrumentation for quantitative metering points in Longship project. Carbon capture, liquefaction and interim storage at Capture, ship transport at Transport and interim storage, pumping and injection into well at Storage. The figure shows where the critical points CO2 is measured in the chain. The inventory transfer of CO2 is based on tank level measurement (blue boxes).

All field instruments are regularly calibrated to ensure measurement reliability and compliance with international standards. This is especially important for regulatory reporting and ownership transfers (land-to-ship and ship-to-land).

Example of common instrumentation:

Quantity and flow measurement

- Coriolis meter: Provide highly accurate and direct measurements of the amount of CO_2 passing through a pipe. Used during loading and unloading of CO_2 ships to ensure accurate transfer between parties.
- Venturi meter: used at the wellhead to measure the amount of CO_2 injected into the storage site. These utilize the pressure difference before and after a pipe narrowing to calculate fluid flow rate and ensure accurate injection volume monitoring.

Quality control:
To ensure that the CO_2 being captured, transported, and stored meets the required quality standards, it is important to accurately determine the composition of the gas or liquid. This is done using both online analysers (in the field) and offline analysers (in the laboratory).

- *Online analysers*: Operate in real-time within the plant and display results on control room screens. They detect both major gas components and trace impurities down to ppm and ppb levels.

- FTIR (Fourier Transform Infrared Spectroscopy): Measures gas components based on infrared light absorption with high sensitivity.
- Mass spectrometers (IMR-MS, EI-MS): Analyse gas molecules by mass and charge.
- Zirconia sensors: Precisely measure oxygen (O_2) levels.
- Specialized mercury analysis: Used when trace mercury monitoring is required.

- *Offline analysers*: Laboratory-based, usually using gas chromatography (GC) for detailed composition analysis and calibration of online instruments.

Leak Detection and Monitoring:
Several techniques are used to monitor the well, surface, and even from space to ensure stored CO_2 remains underground. Monitoring takes place in three main zones:

- *Atmospheric monitoring (from sea surface upward)*: Satellite-based radar (e.g., InSAR) used to detect minor ground movements possibly linked to CO_2 behaviour underground.
- *Surface and near-surface (from seabed to sea surface)*: Seismic imaging (4D seismic) tracks CO_2 movement in the reservoir over time.
- *Subsurface monitoring (below seabed)*: Micro seismic measurements using sensitive listening devices along the well to detect underground movement.

Summary

Accurate measurement is vital for CCS to function effectively as a climate measure. Reliable data on quantity, quality, and safety are essential to attract private investment, support regulatory oversight, and ensure public trust in the security of CO_2 storage.
Standardized measurement methods embedded in legislation and international agreements provide a clear framework for CO_2 trading, clarifying ownership and responsibility. Technological precision is therefore critical to ensure every ton of CO_2 is documented, delivering both climate and economic value.

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