Document No.: NC04-NOCE-A-RA-0018			Rev.: 02	Page: 1 of 27
Originator: NOCE	Tag.No.:	System No.:	Area Code:	
Classification Code: Confidential / Open				

Rev.	Issue date	Description	Made by:	Checked by:	Disc. Appr.	Proj. Appr.
Draft	15.06.25	Issued for Information	TG/ASP	-		TG
01	04.08.2026	Issued for information	TG/ASP	-		TG
02	14.10.2026	Issued for information	TG/ASP	-		TG

Brevik CCS

Lessons Learned Report 2H2025 & 1H2026

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Revisions to this document

Rev. no.	Revisions in chapter	Description
01		First version
02	10.3	Minor update

Attachments to this document

Annex no.	Description
01	Lessons learned presentation. Please note that these slides are normally used as a presentation to externals and internals. Some of the slides may therefore be difficult to read on their own, however we have added the presentation as supplementary information to this report.

Executive Summary

The Brevik CCS project represents the world's first full-scale carbon capture facility integrated with a cement plant and provides valuable experience for future industrial carbon capture projects. This report summarizes the key lessons learned during the period from the second half of 2025 through June 2026, covering final commissioning activities, start-up, performance testing, and the first months of commercial operation.

The facility successfully completed the Acceptance Test in November 2025 and has subsequently operated as an integrated part of the Brevik cement plant. During this period, the organization has gained extensive practical experience related to operation, maintenance, commissioning, safety, regulatory compliance, and integration between a carbon capture facility and an existing industrial process plant.

A key conclusion from the project is that carbon capture technology based on amine absorption can be successfully implemented and operated at industrial scale on cement kiln flue gas. The project has demonstrated that the technology is capable of achieving design capture rates, while also highlighting the importance of continuous optimization during the first years of operation. Technical challenges encountered after start-up have generally been resolved through systematic troubleshooting, close cooperation with technology suppliers, and active involvement from operational personnel.

The project has also demonstrated that successful delivery of a CCS facility depends on much more than process technology alone. Early establishment of the operating organization, extensive operator training, realistic commissioning planning, and strong integration between the host facility and the CCS plant have proven to be critical success factors. Particular value was obtained from simulator-based operator training, involvement of operators during construction and commissioning, and the use of dedicated system leads throughout the commissioning phase.

Several lessons relate to the integration between the cement plant and the capture facility. Areas such as instrument air quality, waste heat recovery, dust handling, utility systems, and operational interfaces had a greater impact on overall performance than initially anticipated. Future projects should therefore devote significant attention to the condition, capacity, and operational robustness of existing plant infrastructure during the early design stages.

The project further demonstrated the importance of robust management systems for safety, regulatory compliance, and maintenance. Operating a CCS facility introduces new challenges related to CO_2 exposure, steam systems, pressurized equipment, functional safety systems, and permit-to-work processes. Early engagement with regulators, thorough understanding of applicable legislation, and establishment of maintenance and inspection programs are essential for successful operation.

From a project execution perspective, the experience confirms that commissioning and operational readiness activities require significantly more effort and resources than is typically anticipated in traditional industrial projects. Clear definitions of Mechanical Completion criteria, detailed planning of commissioning activities, and sufficient staffing of specialized functions are critical to achieving successful start-up and smooth transition into operations.

Overall, the Brevik CCS project has demonstrated that full-scale carbon capture from the cement industry is technically feasible and can be operated safely and effectively. The lessons presented in this report are intended to support future CCS developments by identifying practical challenges, highlighting successful approaches, and contributing to cost reduction, risk reduction, and improved project execution across the emerging carbon capture industry.

1 Purpose

This report is a summary of the lessons learned during the period from the second half of 2025 until June 15th, 2026 (including June 2025) of the Brevik CCS project.

This report has collected the lessons learned from:

- Brevik CCS project team members
- Brevik Plant personnel
- Heidelberg Materials Northern Europe
- Heidelberg Materials – Competence Center Cement
- Project Partners
- Gassnova

The input was further refined down to the key lessons learned to be shared outside the project organization.

2 Project Progress Overview

On a high level, the following has been accomplished on the Brevik CCS project in the past one year:

- 2 lost time injuries occurred on site in 2026as of end of June 15th 2026, bringing the total in the project to 6 LTI´s
- As of the end of May 2026 1.416.195 manhours had been worked on the project.
- Acceptance test with respect to Grant Support Agreement was successfully conducted early November 2025 and.
- GM-07 (Completion certificate) has been approved with effect from 19th of December 2025.
- The New Maintenance Center (NMC) has been constructed and moved into. The building houses the new combined control room, changing rooms, mechanical workshops, offices, meeting rooms and a new canteen The building is also essential in relation to Brevik CCS's benefit realization obligation as it also houses a modern conference room.

Figure 1. Site photo December 13th, 2023

Figure 2.Site photo May 2026

The following specific challenges and/or changes in the project scope were encountered during –the past year:

- The war in Ukraine has continued but has had no further impact on the project.

Since May 2025, operation has been characterized by several technical challenges both on the Cement plant, in the interface between the cement plant and the CCS, and in the CCS plant itself. Fixing technical issues has had high priority during this period to maximize captured volume. Hence,

many production stops have occurred, and production volume in 2025 ended significantly below budget, while production volumes are slightly above budget by the middle of June 2026

3 Technical set-up and performance

This section reviews technical aspects of the project, including design documentation, utility systems, and operator training. It focuses on technical challenges faced and the solutions implemented to ensure successful commissioning, start up and operation.

3.1 Cement plant P&ID's

The cement plant P&ID's should be updated at the start of project. This was not the case in Brevik CCS which created delays and confusion during the design stage and during commissioning. It is recommended that cement plant P&ID's are up to date and with required level of detail to indicate key instrumentation and to show battery limits with CCS plant and they should be controlled by the Engineering Manager within the project or have a clear focal point to coordinate any updates required throughout the project from the cement plant.

3.2 Integration between Cement Plant and CCS facility

The integration between the existing plant and the capture plant was well managed with a minimum of problems due to the high number of local Brevik cement plant personnel that were integrated into the commissioning and start up team. While this may not be possible in other locations, having people on the project team that have worked in the existing plant for years and know intimately the people helps to minimize problems.

3.3 Poor performance of Electrostatic Precipitator (EP)

Despite a lot of effort to fix the performance of electrostatic precipitator 3 on string 2 of the cement plant the filter is still not performing as per design (100 mg/Nm3). Current performance is well below the promised design threshold which results in a higher dust-load entering the waste heat recovery boilers on string 2 likely resulting in a higher degree of dust scaling in the boiler tubes reducing efficiency.

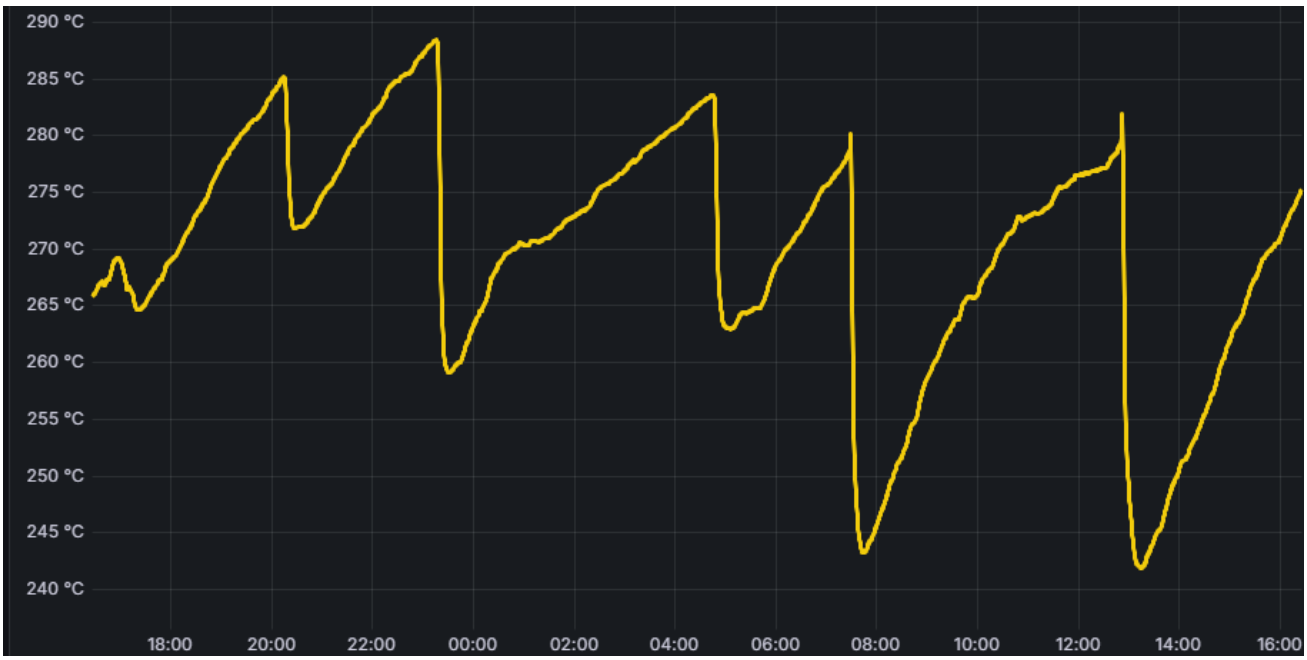
While the reason for the poor performance of EP is not completely clear, factors like high operation temperatures, no use of water injection in the gas conditioning towers, sticky dust and some mechanical errors during installation of the filter are contributing factors. Generally speaking, high flue-gas temperatures and low water content of the flue-gas are well known to decrease the performance of ESP's, which has also been observed on this project. This was a major discussion point during contract negotiations for this package, and the supplier confirmed and documented that they had vast experience with kind of operational conditions, and hundreds of similar projects were already successfully executed.

Improving filter performance will be ongoing throughout 2026 and probably also well into 2027 as most changes and modifications require shutting down the cement plant.

3.4 Cleaning of waste heat recovery boilers

Relatively early during the start-up phase it was discovered that the heat recovery of waste heat recovery boilers on string 1 and string 2 of the cement plant could be increased by injecting relatively coarse clinker dust upstream of the boilers. As the clinker dust is coarse and abrasive it removes some of the scaling in the pipes thereby increasing the heat output.

Currently a few buckets of clinker dust are manually injected into fresh air dampers 3 – 6 times a day sometimes decreasing the outlet temperature of a boiler unit with 30 – 40 °C with a steady heat input:



To reduce the tedious work to manually inject the dust and increase the efficiency work is ongoing to automate this injection using a silo-based injection system. The first system on the boiler system on string 2 is expected to go into operation in July 2026. As the injection system will be fully automated the injection time, injection rate and injection frequency can be controlled and adjusted to achieve the most optimal boiler efficiency. Increasing boiler efficiency is important in relation to reducing the use of the electrical boiler and thereby the overall power consumption for capturing CO2.

It is also assumed that there will be an added benefit in timing the clinker injection with the operation of the sound horns which is currently not possible when injecting manually.

Using infrasound horns for cleaning of WHRU's during operation has been crucial for acceptance heat recovery performance. On both flue gas WHRU's, the infrasound horns have been upgraded to a larger size than originally, which seems to be successful. Be aware that any loss of heat recovery will negatively impact use of electrical boiler or capture rate – both representing very significant success factors for the project.

3.5 Instrument air

Cement instrument air quality was insufficient for the required quality of air both in regard to pressure and dew point for the capture plant to function correctly. A higher standard is needed to be delivered reliably for operation of the CCS facility. The cement industry in general is weak in this area as compressed air is not seen as a source of problems for a standard cement plant. It is recommended that an independent instrument air system be designed and installed for the CCS plant and not rely on any existing systems within the cement plant unless the existing system is in a good and documented condition with surplus capacity. Alternatively, to ensure adequate capacity and delivery quality of the existing air compressor station well in advance (min 1 year earlier) and establish a direct pipe connection to the CCS-plant to ensure availability and not to rely on decades old piping.

Maintenance and operation routines of the air compressors must also be reviewed to ensure that air quality, compressor availability and system efficiency are continuously monitored and maintained. At Brevik Plant there has earlier not been any tight control of dew point as it did not have high importance with existing equipment.

During revamping of the current legacy instrument air infrastructure, the following issues were discovered:

- A 10-m3 air receiver was installed on the instrument air system reducing small pressure fluctuations.
- Most valves in service on compressed air were globe valves which have high pressure drops compared to gate valves. Such valves were replaced in compressor room 2 and on the main distribution manifold for instrument air in the plant. This initiative further helped to reduce power consumption for production of compressed air.
- A new main line will be installed as the current main instrument air pipe supplying the cement plant and the CCS-facility were several times overutilized resulting in high pressure drops translating into higher power consumption for production of the air required by consumers.
- Flow meters will also be installed on all branch lines from the instrument air main line providing full transparency on air consumption in different areas of the plant including the CCS-plant.

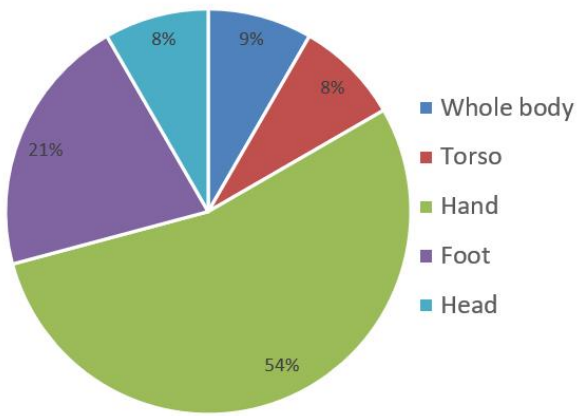
Generally speaking, instrument air and plant air as a whole is often overlooked in the cement industry, as energy consumption is low compared to other consumers such as the pyro-system and mills.

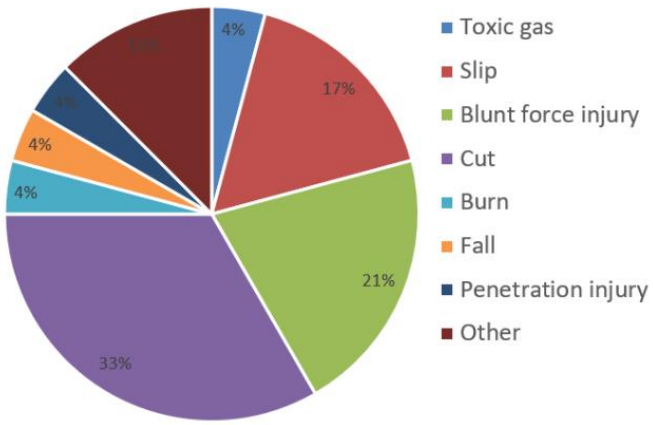
4 Project Management and Execution

This section examines the project management strategies and execution methods used, with a sole focus on health and safety as the other aspects of project management has been covered in the previous reports.

4.1 Health and safety

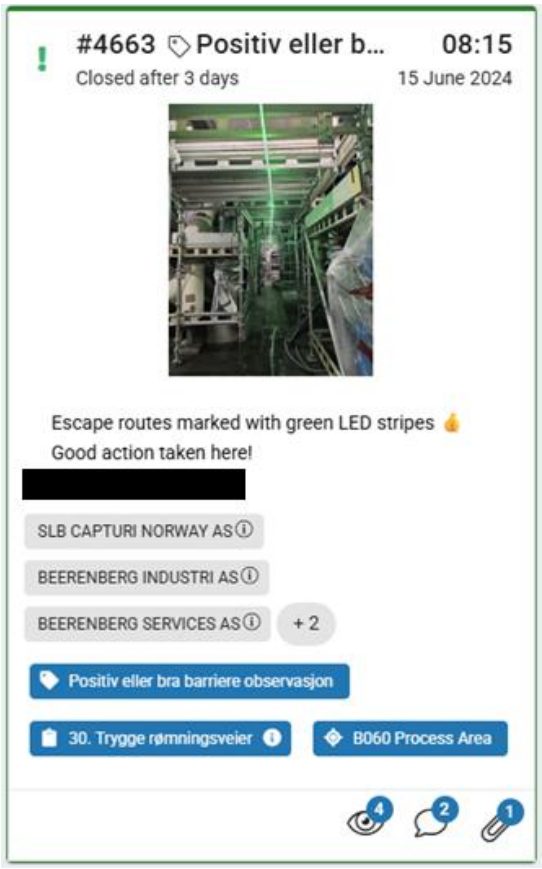
Overall, the health and safety performance on Brevik CCS has been good. The first incident (PFI, LTI, MTI, FAI) happened after 255.000+ hours worked during a phase with mostly civil works. The first LTI happened after 464.000+ hours worked and was due to a slip due to ice (sprained foot). In total 1.416.195 hours have been worked. There has been reported 24 accidents resulting in injury. The worst injuries have been a finger crushed between concrete barriers and partial amputation of two fingers during closure of truck tailgate. The accidents resulting in injury can be categories in the following groups:





All in all, 5.759 observations have been made by contractors and owner in our mobile-app based system to track HSE-issues. The transparent attitude to HSE is assumed to be a key contributor to the good health and safety performance. Probably 70 % of observations have been made by contractors (foreman and workers) and around 13 % of all observations are positive observations. In

general, it has been a target to promote the use of positive observations to encourage people to do the right things from a safety perspective. An example of a positive observation promoting a high HSE-performance can be seen here:



4.1.1 Confined space incident in the CO_2-compressor room 21.08.2025 (MTI / PFI)

Work in CO_2-scrubber 6.2 was ongoing when a CCS engineer informally entered the vessel to inspect and take photos. Despite known CO_2 fluctuations, the engineer held his breath but likely inhaled, seemed like he lost consciousness, and was pulled out by colleagues. He recovered after about a minute and were later discharged from hospital the same day without any injuries.

Root causes include non-compliance with permits, underestimation of CO_2-hazards, and insufficient confined space and safety training, requiring clearer procedures and improved competence.

A key lessons learned in the above is the part about underestimation of the danger CO_2 pose in elevated concentrations. While the management and process specialist had firm knowledge about the dangers of CO_2 a culture had slowly evolved that very brief inspections could be done without breathing equipment or other precautionary initiatives. The above incident served as a wake-up call that this this practise should cease, and work permits also must cover even brief inspections to avoid any future incidents. Operation procedures have been revised and strengthened as result of this incident.

It is important to underline that safety has been a firm focus all the time during commissioning and operation – the mentioned incident must therefore be understood as a deviation in an otherwise very rigid approach to HSE.

4.2 Mechanical Completion (MC)

The definition of MC needs to be detailed, and the roles and responsibilities of each party need to be identified early. Due to the lack of experience of HM on what specifically is required by MC and the accelerated handover schedule this could have been managed much better. For future projects the following recommendations are proposed:

- Define specifically how complete the insulation needs to be done for critical path areas. Can the installation be installed while the system is in operation? What scaffolding will be needed? Lack of definition in these areas created extra work and inefficiencies.
- Define the required cleanliness of pipes. How to validate cleanliness? Method of cleaning pipes? No clear definition was given, leaving it open to interpretation.
- Define the required cleanliness of area in general. How much scaffolding can remain? Dirt on tops of pipe? No clear definition was given, leaving it open to interpretation.
- Define what construction continues in areas that are in operation. And assess HSE implications of parallel construction and commissioning if that is intended to be done in the project. Construction workers must be effectively informed that they are working on a process plant and not in a construction site anymore if that is the case, and access to areas and work permit system has to be regulated by the commissioning/operation team, which also requires additional resources.
- Prior to handover, single area walks with all disciplines shall be organized. Avoid having segregated area walks only by company or some of the contractors as this leads to misalignment and re-work.

It is recommended that Insulation boxes are only installed after leak checking of the valve flanges. The requirement for their installation as part of MC was not sufficiently clear so that rework was required when they had to be removed as part of the leak testing. This confusion was primarily due to schedule acceleration and achievement of milestone commitments. Special attention to be paid to packages which come pre-assembled as a skid. Either it is inspected by Company at the fabrication site before and during leak test, or flanges must be visible at site to perform leak test at site.

4.3 Leak test vs. Leak check

Contract specified leak check and Contractor used that to indicate that they did not need to perform leak test as part of MC. Company had to carry out such tests, especially for high-pressure systems where HSE concerns were highest.

4.4 Completion Specialist/Pressure testing Lesson learned

The following lessons learned were provided by the company that was the completion specialist for the oil industry specializing in pipe pressure testing, cleaning and general pipe construction /commissioning activities.

- The piping design should consider pressure testing or cleaning. Very complex pipe routing, no drains – which made their work more time consuming and expensive. It is recommended to involve the use of a specialist completion services company to review the piping design early so that small changes can be made at low cost and give tips to make the completion work easier, such as.
    - shifting reducer locations to allow for longer straight sections for cleaning (soft pig – very inexpensive method)
    - adding drain points so that draining after pressure testing is easier.
    - review the pressure testing concept – use of flanges, vs. N2 testing, vs. golden welds, etc…
- Define the pipe cleanliness required for the different systems. From “remove loose debris” to “bare metal” scale. The question “what is clean enough?” should be answered early as it will impact the pressure testing method.

- Pipe dryness – should also be defined early – this was left too long in Brevik and many meetings were held just to agree on this. Easy to include statements early in the project but when it becomes critical path everyone argues over little details.
- "Golden weld" or a weld that doesn´t need pressure testing due to the higher weld testing requirement – should be considered on pipelines that with highest man hours for insulation installation. This is due to the delays the project is faced with the requirement pressure testing must be done before it is insulated.

4.5 Commissioning

Early commissioning of utilities - The early commissioning of any available equipment helped to provide the necessary time to rectify any operational issues such as the demineralized water system, the effluent water treatment, potable water supply and the instrument air system. The more these systems are separated (distance and electrically) from other systems the easier the early commissioning is.

System leads - the commissioning organization that was structured into System Leads for the respective main commissioning systems of: Steam and Condensate, CO2 capture plant (amine), CO2 compression and liquefaction, Integration with the cement plant and Utilities systems (instrument air, plant air, cooling water, potable water, effluent water treatment plant). This organization was effective, and the following lessons were noted.

- Recommended to use Owner´s personnel for these key positions and not 3rd party contractors. The level of commitment needed is quite high as significant overtime will be worked. In addition, the use of owner´s personnel ensures that the valuable knowledge gained during commissioning is not lost.
- It is recommended that each area leader is assigned a supporting project engineer to assist with the workload. There is a high demand for documenting and reporting issues to the contractor during this phase, in parallel to operations that require more than one person per system to be effectively managed. For this assignment to be successful, the person should be assigned early in the project (during cold commissioning) and remain on site for the duration of the hot commissioning.
- Where possible it is helpful to embed qualified plant personnel into the project team and provide replacements in the cement plant operation. Bringing in either external personnel or engineers from head office are more expensive and less effective often due to having to work away from home for long periods.
- The use of key experts was critical on the project and their specialized knowledge greatly advanced the project during critical periods. It is recommended that these experts are identified early in the project and integrated into the commissioning team.

Winter conditions - the identified frost risk early in the project was quite valid and only with special attention to the risk was it mitigated. In addition, the warm winter also greatly helped the situation, and if it was a colder winter the extra efforts would not have been sufficient.

Pump seal failures - the seals failed on 4 pumps and although this was seen as an unusual event by the supplier, it is recommended that in future projects standard seals are selected (rather than special ones with no spares) and sufficient spares are in stock.

CO2 Compressor – alignment of inlet and outlet pipes to compressor took considerably longer than planned (6 extra weeks). Due to the very high speeds of the integrally geared compressor, no stress can be transmitted to the inlet and outlet flanges of the 7 stage integrally geared centrifugal compressor as they may distort the gearbox casing. In addition, the pipes connected to the compressor must allow for thermal expansion which makes it difficult to check the loading until after the system has been run and heated up. The issue is well known within the compressor industry and should be considered a project risk despite limited visibility during vendor evaluations. Similar problems were reported at Boundary Dam CCS project and the Petra Nova project but even

knowing this in advance did not help as this is a known risk that the compressor companies accept. Therefore, the recommendation is that sufficient time is allocated in the schedule for this activity and it is highlighted as a known risk.

Cold commissioning software system – suggest adopting the contractor´s and agreeing on costs and access to it early. HM tried to use a different system which didn´t work well with contractors. Risks are that if the work is subcontracted to a large construction company, they also have their own systems – which need to talk to with selected one.

Hot Commissioning Meeting frequency – During the more than 3 months of hot commissioning, a daily 30-minute meeting was held each morning and was attended by up to about 30 people. During the meeting the upcoming activities for the day were discussed and any new developments from the day before. A short email to the attendees was issued after each meeting. See example from March 18, 2025, below:

Responsible	Points of attention **today**
Steam & Condensate	• Sample point is WHRU1 to be checked.
Amine and integration with cement plant	• Check leak in lean amine pump drain. • Assess requirement to flush lean/rich exchanger prior visit of Kelvion, next week. • Need to implement clinker dust injection upstream ID fan.
System Lead Comp. & Liq.	• MAN expert to be at site today. • Actuated valve in B060 turned and tested yesterday. Turning of actuated valve in B340 tomorrow, preparation starts today. • Leakage in B340 to be investigated again today. • Locking of CO_2 pumps for purging is being investigated with Flowserve. • WW supply to flash vessel to be inspected today. Removal of insulation box coordinate with Aker.
E&I	• HV supply to compressor solved.

Ad-hoc meetings were organized as needed to discuss specific issues with relevant people only. This way, the number of meetings was kept to a minimum, which is desirable in such a busy period.

Co-location of Commissioning teams – Initially in the project each contractor and the owner had their own separate construction trailers for offices, which in addition were several hundred meters apart. This was partly due to the availability of space on site and the lack of trust between the contractual partners. In the final year of the project, the decision was made to combine the offices of the main contractor and the owner. The owner paid for the relocation of the construction trailers and the change was very beneficial for the project communication. Having closer proximity to each other greatly improved speed of communication as well as the level of cooperation between the parties. It is recommended that in future projects this is done as well. In general, eliminating reducing physical barriers creates the sense of one team, while physical barriers promote silos behavior.

4.6 Mechanical Completion Criteria

Avoid grey areas in the MC definition and be clear on who performs what. The following issues were identified during the project:

- Witness testing during any flushing activities on pipes is very difficult
- Drying of LCO2 systems was not explicit in the contract.

- Chemical cleaning of columns packing needed to be done by Contractor but was only possible during commissioning by Company.
- Cleanliness criteria in Cement plants is very low compared to cleanliness criteria in chemical plants needed at MC, both, inside and outside pipe and equipment, but also the floor, etc.
- The contract was not very specific regarding cleanliness; it only mentioned that the plant shall be delivered with a cleanliness level “fit for purpose”. It is recommended to clearly estate in the contract what clean means. Refer to industry standards for example.

4.7 Operator Training

Additional time was required to expose each operator to the startup and shutdown sequences as this was the most challenging situation for them to learn, and they could not be independent until they had the confidence to start up or shut down the plant on their own. It is recommended that the commissioning schedule takes that learning curve into account and allocates sufficient time to allow all shifts to have exposure to startup and shutdown as the commissioning of the different systems progresses.

4.8 Scaffolding

Both the owner and contractor underestimated the quantity of scaffolding. It is recommended to hire more coordinators that have a good understanding of what the trades need to do their work. A person experienced in insulation to guide the scaffolders what insulators need, and someone with piping experience to guide them in what pipe fitters / welders need. The scaffolding was done on a reimbursable rate – and the comment from the workers when the scaffolding was put up in the correct way to do the work was that the work went so much faster.

4.8.1 Scaffolding & Insulation Lessons Learned from contractor

One contractor was responsible for piping and insulation installation on the project site as well as off site in the pre-fab areas. They worked over 900´000 man hours on the project and executed over 11´000 job card packages. Their peak work level was around 15´000 man hours a week in February of 2024 and had people from 12 different countries on the project. The following lessons learned were provided by them;

- Recommend having a small scaffolding team on call to address small modifications to correct issues so that work can continue quickly rather than the full new job system that is used for larger scaffolding work. Scaffolding often didn´t meet worker’s needs – with the levels being at the wrong height or too close to pipes to allow insulation work to begin.
- Scaffolding activities were not included in the schedule at all which made planning for contractors more difficult and it is recommended to include major scaffolding in the schedule.
- Insulation requirements were too detailed and complex, with several different types of insulation systems and products, cladding types and clamps. This led to inefficiency in the work. In addition, it was felt that the requirements were too stringent.

4.9 Quality

Quality was never an issue in the project (HM team had little QA/QC on pipe welding) but a high quality was delivered due to the culture as it comes down to the individuals. HM should not assume this exists elsewhere and ensure proper QA/QC systems are in place.

4.10 Shift hours

The workers were only interested in projects that allowed them to work two weeks on two weeks off. Then they would go to another project during their “off” time. The working shifts need to be planned early in the project as it has a cost and productivity impact. This also has a retention impact and consistency of work crews that contractors should consider in their hiring policy and be aligned early.

4.11 Module Fabrication & Equipment installation lessons learned from contractor

The following lessons learned were provided by the contractor responsible for the installation of the mechanical equipment as well as the structural steel for the modules and pipe support systems.

- Module planning – more tolerance should be planned for when considering the outer dimensions of the modules for the allowable space that they are to be set in. In Brevik they had an allowance of 20 cm and in the end, it cleared by only 5 cm due to module 03 leaning slightly when it was lifted.

Multiple contractors on site required a lot of coordination and often the key messages didn´t get distributed to the site teams. The morning daily meeting was used to basically inform the contractors what was happening that day on site. A recommendation for future projects is to have this information posted online so that it is easier for the different contractors to be informed.

5 Lessons learned from operations

5.1 Pressurized equipment – laws and regulations

PED is the European Pressure Equipment Directive 2014/68/EU. Pressure equipment with an operating pressure greater than 0.5 bar falls under the scope of the Directive and therefore CE marking is required by law

Listing of key elements:

- Pressurized equipment
  - Steam systems
  - CO2 compression
  - LCO2 systems
- PSV's, Gaskets, Flanges, Torques, Bolt specifications, Lubrication of bolts
- CE-certification
  - Declaration of conformity
- Inspection routines for pressurized equipment
- Permit for operation from national authorities
- PED requirements for operation and maintenance

Summary of focused PED-elements for operation:

- Operation of steam systems has very specific legal requirements with comprehensive control scheme on daily, weekly, monthly and annual basis
- All PSV's (75-80 in Brevik CCS) must be recalibrated before startup and then annually (possible to extend after few years of experience)
  - Comprehensive process. Some are small, some are large (1-300 kg)
  - Specialized job (dismantling, handling, calibration, re-certification, re-installation)
- «Gaskets» is a surprisingly complicated and critical matter
  - Many types, dimensions, standards and pressure classes
  - Type of gasket must match type of flange
  - Bolt specification must match torque, flange type, pressure class and gasket type
  - Type of bolt lubrication is crucial for correct torque
  - Gaskets must be handled as spare parts with BOM, not as a consumable
- Declaration of conformity required from system suppliers
- Interpretation of laws and regulations is not straight forward and must be formally verified from relevant national authorities
- Very strong requirements on Safety Instrumented Function (SIF) and Safety Integrity Level (SIL) requires comprehensive testing. Tests must be witnessed by third party

PED must be thoroughly studied to comply with requirements for operation and maintenance of the CCS facilities. Internal procedures and routines must be worked out accordingly.

5.2 SIF and SIL - Requirement for Permit to operate

The terms SIF and SIL are central within functional safety in the process industry and follow international standards such as IEC 61511

- SIF (Safety Instrumented Function):
  - This is the actual safety function that must perform a specific task to bring a process to a safe state when a hazardous situation occurs. A SIF typically consists of a sensor, a logic unit (e.g., a PLC), and a final element (e.g., a valve).
- SIL (Safety Integrity Level):
  - This is a measure of the reliability or performance level of the safety function (SIF). It indicates how much risk reduction the function must provide.

Be aware that SIF and SIL requirements are strict and comprehensive and crucial for obtaining operational permit. Maintenance routines for regular SIF and SIL follow-up are required for operation.

5.3 Gaskets

A major experience from operation has been importance of control of gaskets. The plant has a very large number of gaskets in all kinds of classes, standards and dimensions, and it is a critical importance to make sure the exact right kind of gasket is always used. Operating under very high pressures and with hazardous chemicals, leakages or gaskets blow-outs is highly dangerous and must be avoided. Generally, spare gaskets must be treated as spare parts, and not as consumables. Every gasket should be properly marked with all relevant key data.

Just as important as quality of gaskets, is installation specifications like torques, and type of thread lubrication, and of course fitters' competence.

It is our experience that hydraulic tool for fastening and torquing of flanges is highly valuable, preferably with double key in order to fasten and torque the flanges in an optimal way.

5.4 Valves

A full-scale CCS plant contains a very large number (thousands) of valves, and the plant is generally very sensitive to imperfect operation of every valve. The valves operate under very variable conditions and with very different media. Make sure the vendors can document successful experience with similar operational conditions, especially with LCO_2. Brevik CCS have experienced major problems with valves in general and strongly recommends very high focus on this during detail engineering and procurement.

5.5 Integration with cement plant

Major challenges were experienced with the cement plant integration, such as:

- Increased temperatures from preheaters through GCT's, ID-fans, ducts and filters. Major challenges were faced from the fact that the dust became sticky at the new running conditions, causing major problems with ESP performance and vibrations on ID fans. GCT's were replaced earlier in the project to be able to withstand higher pressure and suctions.
- Higher temperature in dusts coming out of the filters is causing different running conditions for downstream mechanical conveyors. Make sure this issue is being properly reviewed.
- Instrument air quality. The CCS plant is far more sensitive to poor instrument air quality than the cement plant. Make sure the situation is properly reviewed.
- False air ingress is major issue since any leak will impact the capturing capacity and heat recovery negatively. Extraordinary attention must be given to reviewing the situation.

5.6 Water entrainment from scrubbers

Brevik CCS experienced major issues with water entrainment from one scrubber in the heat recovery system for the compressor. An additional scrubber had to be installed downstream the problematic one, solving the problem after several months of troublesome and reduced capturing performance.

5.7 Health and Safety

New hazards coming from CCS plant operation:

- Exposure of CO_2 in dangerous concentrations
- Hot and pressurized steam in very large quantities
- CO_2 under very high pressure (up to >70 bar)
- LCO_2 under high pressure
- Potentially dry ice (frozen CO_2) at -80°C
- Chemicals
  - Amine products
  - Caustic Soda (50%)
  - (Flue gas condensate)
  - Others in minor quantities

Relationship Between CO_2 Concentration and Mortality:

CO_2 Level	Concentration	Exposure Time	Health Effect
0.04 %	400 ppm	—	Normal outdoor air
0.1–0.2 %	1,000–2,000 ppm	Prolonged	Drowsiness, reduced concentration
0.2–0.5 %	2,000–5,000 ppm	Hours	Headaches, fatigue, nausea
0.5 %	5,000 ppm	8-hour TWA	OSHA/NIOSH permissible exposure limit
4 %	40,000 ppm	Minutes	IDLH – Immediately dangerous to life or health
4–5 %	40,000–50,000 ppm	Minutes	Headache, dizziness, elevated blood pressure, dyspnea
6 %	60,000 ppm	1–2 min	Visual/hearing disturbances, tremors
7–10 %	70,000–100,000 ppm	< 3 min	Rapid unconsciousness, severe neurological symptoms
10–15 %	100,000–150,000 ppm	1–3 min	Convulsions, unconsciousness
>17–30 %	170,000–300,000 ppm	< 1 min	Death due to asphyxiation (displacement of oxygen)

Key learning points when it comes to CO_2 exposure:

- Very steep curve from harmless to lethal
  - A person normally exhales 4% of CO2 but spending 30 minutes in 7% concentration can potentially be lethal
- CO_2 is 50% more heavy than air – Low points are dangerous
- Concentration can by anything up to 100%. Representative measurement is very difficult
- Strict procedures for presence inside the process areas must be worked out

5.8 Digital Work Permit System – Enablon

The complexity related to safe working conditions during maintenance activities, required implementation of a digital Work Permit System:

- Implementation of Enablon work permit system has been successful
- Digital WP-systems significantly improves safety for maintenance operations
- Enablon has fully met our expectations

The below flow chart shows the implemented work permit procedure

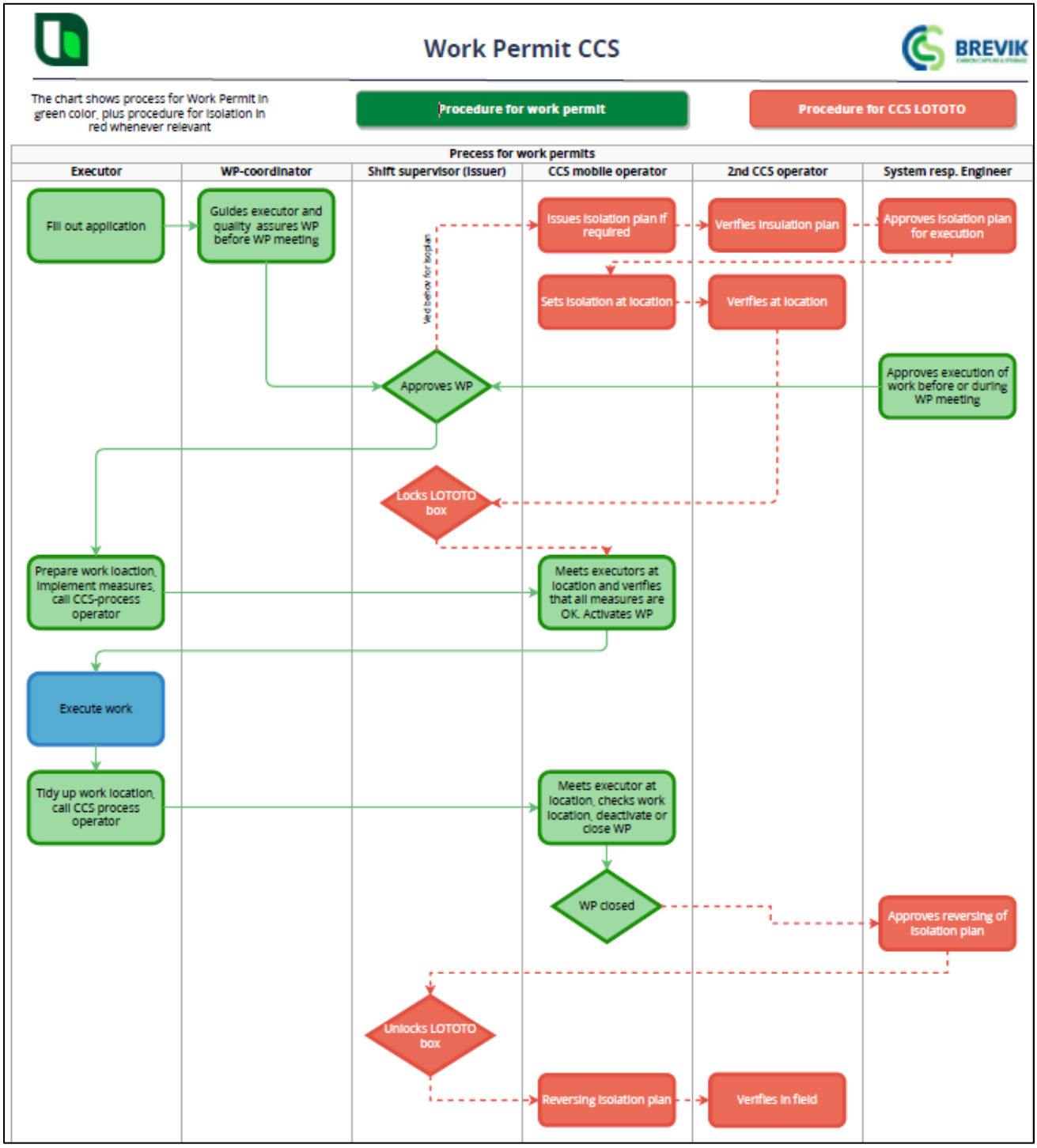


Figure 3 Work Permit Procedure

5.9 Tag-system

- Make sure not to end up with a double tag system. In Brevik CCS we have decided both to use the main Contractor's tag system but also to use HM Brevik Plant's own system as this was preferred by E&I. This adds extra bureaucracy and increases the risk of confusion and misunderstandings.
- Tags, P&ID's, procedures, programs and Process Control System are tied together and must harmonize perfectly

6 Cement culture meets oil&gas culture

We can only mention here that the cultural differences between cement business and oil&gas business is major. In a CCS project like ours, these two cultures meet since CCS technology is still very much dominated by oil &gas culture and philosophy. The most significant differences are being met in all HSE-related processes in all phases of the project, and our experience is that Oil and gas standards strongly influence the design philosophy and execution methodology of CCS projects. Although the requirements at times feel overwhelming, our general experience is that complying is crucial for successful execution of the project and safe operation of the plant. However, it is a fact that a CCS plant differs significantly from oil and gas installations due to lack of inflammable and explosive hydrocarbons, which for sure enables significant simplifications- and saving potentials compared to a traditional oil&gas installation.

7 Organization and Staffing

It is strongly recommended to begin planning the operational organization at an early stage of the project. Significant resources are required both for Preparation for Operations and for the future operating organization. Early in the project, a dedicated staffing study was developed, including organizational structure, staffing requirements, job descriptions, and a recruitment timeline. This document proved highly valuable and was updated several times throughout the construction phase to reflect project developments and evolving needs.

A key early decision is whether operational support agreements will be established with technology suppliers, as this can significantly influence the organizational design and staffing strategy. In our case, operational support agreements were established with the two most critical technology providers. Negotiating and finalizing these agreements was a lengthy process, requiring approximately two years to complete.

7.1 Key Leadership Positions

The first operational position recruited was the Operations Manager, who joined approximately 18 months before Mechanical Completion (MC). The role was filled internally from the project organization. The extensive preparation required for commissioning, start-up, and operations demonstrated that this timing was appropriate. For similar projects, recruiting an Operations Manager at least 18 months before MC is strongly recommended.

Commissioning Manager was recruited approximately three years before MC. Early appointment of this role proved essential, ensuring that commissioning requirements were incorporated into the plant design from an early stage. Effective commissioning planning requires specialized expertise and should be represented throughout the design and construction phases.

7.2 Commissioning Organization

Our experience is that commissioning activities are substantially more extensive than those typically encountered in conventional industrial projects. Establishing a commissioning organization with experienced personnel in key positions is therefore critical.

A successful approach was the implementation of dedicated System Leads, each responsible for a defined group of systems throughout commissioning. In addition to strong leadership, sufficient execution capacity is equally important. Process operators played a significant role in supporting MC, commissioning, and start-up activities. Personnel from the maintenance organization also participated, supporting both project execution and familiarization with the CCS plant. Additional resources from local contractors and service providers were required to meet peak workload demands.

The development of commissioning procedures proved to be particularly resource-intensive. Producing high-quality procedures required extensive reviews, technical discussions, and involvement from experienced specialists.

7.3 Process Operators

Process operators were recruited approximately 12 months before planned MC. In retrospect, this was too early. During certain periods, available work and training activities were insufficient to keep operators fully engaged, leading to frustration and some staff turnover. Personnel attrition should be anticipated in projects of this duration.

Based on our experience, process operators should be recruited approximately six months before MC. It is also advisable to recruit two to four additional operators beyond the minimum operational requirement to account for attrition, absenteeism, and vacation coverage. Maintaining engagement and motivation over an extended pre-operational period requires significant management attention.

Having operators with existing steam-system qualifications is highly beneficial, particularly where boiler operation certificates are required for plant operation.

7.4 CCS Process Engineer

The CCS Process Engineer was recruited approximately six months before the process operators. This timing proved appropriate, as operator training requires substantial preparation. In addition to training responsibilities, the Process Engineer was responsible for developing and operating the Operator Training Simulator (OTS). Throughout the preparation phase, this role proved critical to operator readiness and operational preparation.

7.5 Maintenance Organization

The Maintenance Engineer was recruited approximately ten months before MC. The scale of maintenance preparation was significantly greater than initially anticipated, particularly the development and population of the SAP maintenance management system.

Based on our experience, establishing a fully functional maintenance structure in SAP requires approximately five man-years of effort. In addition to preparing maintenance strategies and procedures, the Maintenance Engineer was responsible for spare parts procurement and defining maintenance execution processes for the operational phase. This role requires substantial time, experience, and technical competence.

Additional maintenance personnel were recruited four to six months before MC. These individuals participated in training programs while supporting MC and commissioning activities. Two preventive maintenance technicians were transferred internally from the cement plant and assigned to the CCS organization. Reporting to the Maintenance Engineer, they are responsible for executing preventive maintenance activities generated through the SAP system.

7.6 Operations Engineer

The Operations Engineer was recruited approximately four months before MC. Responsibilities included developing operating procedures, work processes, and operational routines. The role also included implementation of the work permit system in parallel with commissioning activities. As this was a digital solution developed in cooperation with an external supplier, the implementation represented a significant project in its own right.

Two more operation engineers were onboarded closer to startup, where one is dedicated to operation of the steam systems.

7.7 Laboratory Engineer

The Laboratory Engineer was recruited approximately four months before MC, which proved to be an appropriate timeline. Responsibilities included establishing the CCS laboratory, developing laboratory procedures and routines, procuring equipment and consumables, and preparing analytical capabilities required for operation.

The role also provided important support during commissioning through the establishment of test arrangements and execution of process analyses.

7.8 Key Lesson Learned

Early establishment of the operational organization, recruitment of key leadership and technical positions well ahead of MC, and realistic planning of commissioning and maintenance preparation activities are essential for successful project execution. While specialist positions should be recruited early, process operator recruitment should be carefully timed to balance training needs with personnel engagement and retention.

8 Operator training

Training process operators has been a significant part of the activities during the preparation for operation. We recruited a CCS engineer, a process engineer who already had extensive experience with the operation of amine plants. This expertise was crucial in training of the process operators. All the process operators hired, had formal education as skilled operators. They came from various industries and brought a wide range of experience and working cultures into the group. In the initial phase, the process operators were introduced to both the cement plant and CCS. The training content became increasingly advanced and detailed over time. We called this level "basic training," which lasted for about 2 months. Then, detailed training began. This is more specialized training directly on CCS technology, section by section. Much of the training was done internally with our own experts, but a lot was also done with external suppliers of various technologies. Most of the training was conducted at the factory.

The next phase of training we called "special training." This includes, among other things, simulator training. During the simulator sessions, procedures were reviewed, tested, and revised. Many adjustments were discovered during this phase, and both procedures and PLC programs underwent many changes. It proved to be very important to have dedicated personnel as instructors on the simulator. The instructor's role was practically extended to include the design of the control system.

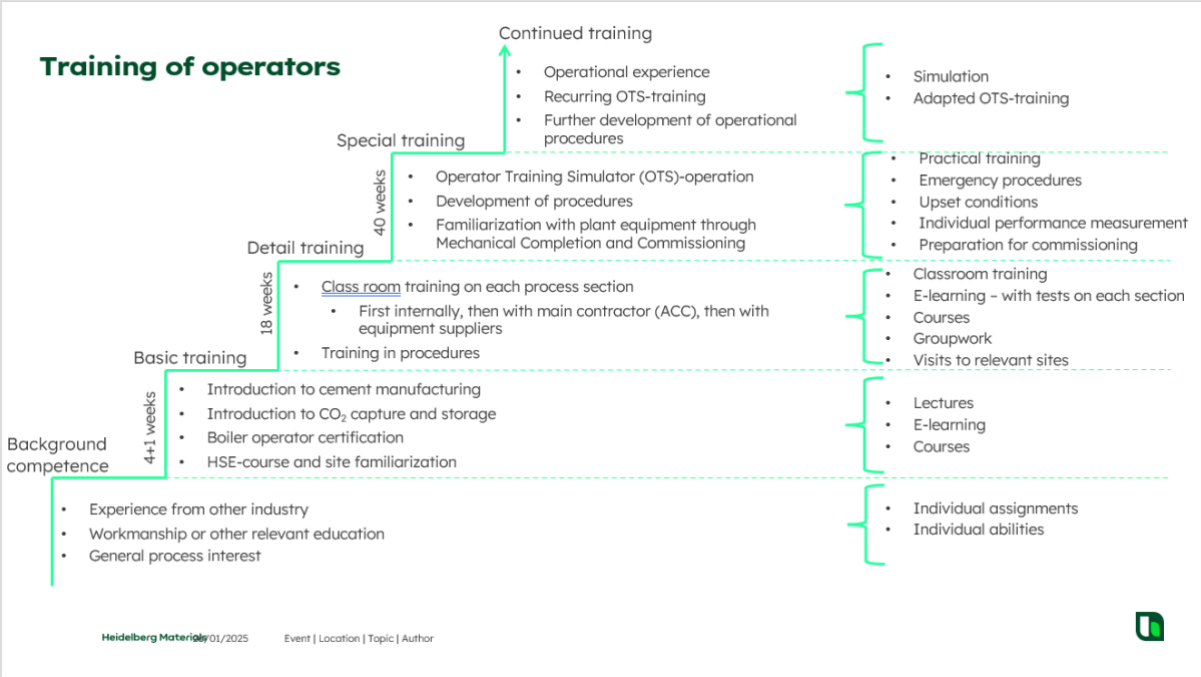


Figure 4. Training program for process operators

The simulator proved to be extremely valuable both for optimizing procedures and the process control system, and for preparing everyone for commissioning, start-up, and operation. A group of 3 operators was assigned to administer the simulator. They prepared training cases for the training of other operators. Additionally, they conducted the training sessions as instructors. Eventually, it became necessary to run the simulator beyond regular working hours, requiring more instructors to rotate. Simulator training started in full about 3 months before MC.
Early in the training, each operator was given special responsibility for their own process section. They delved deeply into their area by gathering all available information and closely following the assembly of their plant. During assembly, each operator closely monitored through daily inspections and marking in P&IDs.

Figure 5. Process operators training on simulator (OTS)

The purpose of distributing operators in this way was primarily to give them the opportunity to train each other. This worked very well. It created great engagement, and it can be easier and more engaging to learn from colleagues than from experts. All operators made extensive presentations on their plant according to a predetermined agenda. From these presentations, they also made videos where they present and explain their work. These videos were archived and have been widely used in training other operators and in new recruitments. These videos will also be useful for future recruitment and training. It is emphasized that each operator should have their own laptop from the start. Additionally, it is important to be aware that they need a place to stay during this period. We also tried using iPads, but it was not very successful in our case.

During the training period, we also placed great emphasis on visiting related industries. In our local area, there is a lot of industry that is very similar to our CCS plant. This includes industries with large compressors, large steam plants, liquefaction processes, large heat exchangers, work permit

systems, and so on. We also visited the Mongstad refinery and the Øygarden reception facility, which will receive our liquid CO_2.

One specific measure that has proven to be very useful was the development of a large P&ID for the entire CCS plant. All P&IDs were combined into this one large P&ID. We have used this in many contexts during the training of both operators and engineers. The figure fits A1 and A0 prints and provides a very good overview of the entire plant, enabling an understanding of how the different processes are connected.

During the training period, the operators were also put on shift work at the cement plant. They were distributed on each shift and worked on shifts for a full period of 5 weeks. Through this, the operators gained in-depth knowledge of the cement plant and got to know colleagues at the company. At the same time, the cement operators received training from the CCS operators on the new plant, both through theoretical training and site visits to familiarize themselves. This was important and successful.

Closer to commissioning, we conducted training for all cement operators on the new plant. These operators will operate some of the equipment that is at the interface between cement and CCS. They have been trained to operate this interface on the simulator. We also consider this part to be very successful and very important as preparation for start-up.

We have also conducted relatively extensive training for shift leaders to familiarize them with the new plant they will be responsible for during operation. This training has been more practical.
The operators have also undergone formal and certified training in the operation of steam systems. This is to obtain a boiler operator certificate, which is required to operate large steam plants like ours. This is a 40-hour course that also requires specific experience to obtain the boiler operator certificate. This certificate is required before the start of hot commissioning. The operators have also taken external courses, especially on valves, pumps, and flange tightening.

A so-called competence book has been created for each operator, detailing the training and experiences each operator must have to be checked out as an independent process operator at the CCS plant. Each point in the competence book must be signed by the operator, the CCS engineer, and the CCS manager before the operator is ready for independent operation of the plant.
About 3 months before MC, a temporary control room was established for the plant. This was necessary for conducting loop testing, which is an extensive and time-consuming process. The operators manned the control room in rotation. This provided good insight into the plant's components and important basic control room training. It is recommended to establish a temporary control room separate from the central control room, as there will be a lot of personnel and noise around the loop testing activity.

Furthermore, the operators were heavily involved in the execution of MC. Inspection and checking of all systems is an extensive and formal process that requires a series of inspections of each component and each line. This process is important for the execution and quality assurance of the MC process but also very educational for each operator.

9 Costs

This section discusses a summary of cost-related lessons, budget variances, cost drivers, and recommendations for more accurate forecasting and cost control in future projects.

9.1 Use of specialized companies for pressure-testing and drying of pipes

While the use of specialized companies can be very beneficial for carbon capture projects they may also come with a high cost. Specifically, it has been noted that pressure-testing and drying of pipes is a work-intensive task often involving companies from the oil & gas sector. As such companies

normally work for an industry where cost is not necessarily the primary focus, they tend to have a high base cost not usual for land-based industry outside oil & gas.

9.2 Contingency for small process adjustments and upgrades

During startup and initial operation, it became clear that some minor changes to the process where required to achieve the projects design capacity, power consumption or similar. Modifications and additions such as a new transport system to electrostatic precipitator 3, injection of clinker dust upstream of the boilers, bigger sound horns for the boilers and installation of isolation valves on amine heat exchangers have been approved and/or implemented.

This cost has been taken from overall Contingency, however future projects should consider allocating cost, in addition to Contingency, for *known unknown* process upgrades, modifications and smaller purchases from the project start. Not everything is a supplier risk and therefore not everything can be claimed rectified on warranty.

10 Environmental impact

This section addresses environmental considerations, including noise management and other impacts observed during startup and operation, along with recommendations for minimizing environmental footprint in similar projects.

10.1 Excessive noise when venting CO_2

Excessive noise when venting CO_2 – no silencers were installed on the CO_2 tank farm as the design considered that this would be required only rarely and, according to the contractor, the valve supplier indicated that the noise level would be below the threshold defined for the project.

To keep noise levels within acceptable limits (max. 40 dBA at nearby residential dwellings) it was necessary to install a silencer. Installing a silencer during installation would not pose a significant extra cost, thus this should be considered in the design for future projects. It is also worth pointing out that especially noise is something which neighbors are fast to complain about which may contribute to a negative attitude towards CCS.

10.2 Noise from fan motors

From the fan motors of all the waste heat recovery boilers a high-pitch noise is being emitted at a specific frequency around 3.150 Hz and 85 dBA. The frequency is in an area where people are especially sensitive, and the noise therefore becomes especially annoying. While the problem is not completely understood, it is assumed that the frequency drive is inducing the noise into the motor which causes parts of the motor to vibrate. Replacing the frequency drives has been tested without any significant change.

The next step will be to replace the motor with one from a different vendor to see if this solves or reduces the problem. If this does not work the only viable solution remaining will be to build an enclosure around the motor to dampen the noise being emitted.

An alternative would have been to procure a frequency drive with a built-in sine filter which may filter out the noise before it is induced into the motor, however such a drive comes at a higher cost and is physically bigger. Unfortunately, there is not enough space in 2 of 3 electrical rooms to accommodate a frequency drive with a bigger footprint.

The recommendation for noise-sensitive projects is to consider either a frequency drive with a sine filter or procuring the fan motor with a noise enclosure from the beginning

10.3 Smell

A very distinct smell has been identified from the absorber stack, and complaints are received from neighbors. A comprehensive study using advanced on-line and off-line analysis has been conducted and conclusion is still pending (May 2026). Main suspect a the very minor component in the group of “Pyrazines”, identified in the flue gas, with concentrations around 100 ppb. This component (and similar) is not toxic but has a unpleasant smell. Testing is still ongoing to find root cause for formation of the component and to identify mitigating actions.

11 Health and safety – operation

This section highlights the health and safety practices adopted, challenges encountered, and the effectiveness of safety culture initiatives, with a focus on regulatory compliance and continuous improvement.

11.1 DSB (Norwegian Directorate for Civil Protection) consent

Consent from DSB is needed for the start-up and operation of the CCS facility. It must be documented that the facility has been constructed/built in accordance with the 2014/68/EU Pressure Equipment Directive (PED) and Regulations on the handling of flammable, reactive and pressurized substances as well as equipment and facilities used for handling

It is also a requirement from the Norwegian authorities that an assessment is carried out by a third party (Notified Body). Both Contractor and Owner chose Kiwa as Notified Body. Based on individual Declaration of Conformity Compliance (DoC) (Samsvarserklæring) for each sub-assembly, component, equipment, etc. and applicable CE-marking, the Completion Inspection Report (Ferdigkontrollrapport) can be prepared. Before the Completion Inspection Report can be made, the DoC for assemblies i.e. Compressor package and Reclaimer package.

The Completion Inspection Report is the final deliverable and includes:

- Design control
- Installation control
- Control of safety critical functions
- In addition to reviewing relevant documents, some physical inspections are required

The following Lessons learned were collected on this subject;

- Obtaining sufficient documentation for the Notified Body, holding meetings, inspections etc. has proven to be more time-consuming and extensive than first thought. In the future, it is important to start this work early and demand a detailed SoW from Notified Body before entering a contract
- Personnel chosen to do the work with the Notified Body should have good knowledge and experience of both Pressure Equipment Directive (PED) and Regulations on the handling of flammable, reactive and pressurized substances as well as equipment and facilities used for handling. HM had insufficient experience with the Pressure Equipment Directive (PED) and in working with the Norwegian authorities.
- Mere days before the start of ship commissioning, the DSB chose not to follow the recommendation of the Notified Body which created additional costs and delays to the project. Due to lack of experience HM was unable to react quickly to address this issue or change its outcome. It is therefore recommended that the project team educates itself early in the project on the specific country requirements for the necessary PED certifications.

11.2 Site Safety

Emphasis has been placed on a good working environment where cooperation and a good tone have been implemented at all levels. This has contributed to an open safety culture where information is not withheld but flows easily to the sources that should have it. Building such a safety

culture has been very successful in the CCS project. Feedback from surveys as well as during safety rounds or inspections indicates the same.

A good safety culture was built in the project by providing the employees with information about transparency in the handling of deviations, by making it clear to the employees that they are not responsible for mistakes but that there are causes that the project will correct, Explaining the learning curve in the event of errors, we also measured the psychosocial working environment monthly. Furthermore, all feedback from employees and the reports of deviations that came into the project were taken seriously. It was important to put this culture in place from the start in the projects and the classroom HSE induction course was used as the trigger for this understanding of safety culture.

With the philosophy of no blaming culture, i.e. finding the root cause and not placing blame on an individual, has worked in an excellent way. The number of registered nonconformities in the project is over 5.750 (middle of June 2026), which is extremely good also by Norwegian standards. The system cannot stand alone. It is paramount that activities in the system are followed up by a HSE-manager or similar. The appointed responsible should however act as a facilitator and promotor; actual creation and closure of issues should be carried out by workers and foremen.

One lesson learned specifically to highlight, as several LTI's on the project has been due to slippery conditions due to snow and ice. The project has primarily been relying on the plant's existing measures to remove snow and ice thereby reducing the risk of trips and falls. After several winters it can be concluded that the plant's existing procedures for snow/ice removal did not suit the projects requirements and sheer number of people on site (450 versus maybe 60 – 80 people normally). Therefore, the project should have had a completely independent setup for snow and ice removal in common areas of the project.

12 Conclusions and Recommendations

The most significant lessons learned that made Brevik CCS an industry success story:

- Early establishment of an operational organization is critical.
- Commissioning effort is substantially larger than anticipated in traditional industrial projects.
- Operator training simulators provide value far beyond training and contribute to control system optimization.
- Integration with the host cement plant has greater impact on performance than initially expected.
- Instrument air quality is a critical success factor.
- Management of pressurized equipment and regulatory compliance requires dedicated expertise.
- Strong local stakeholder engagement contributes significantly to project success.
- CCS-specific safety risks require dedicated organizational competence.