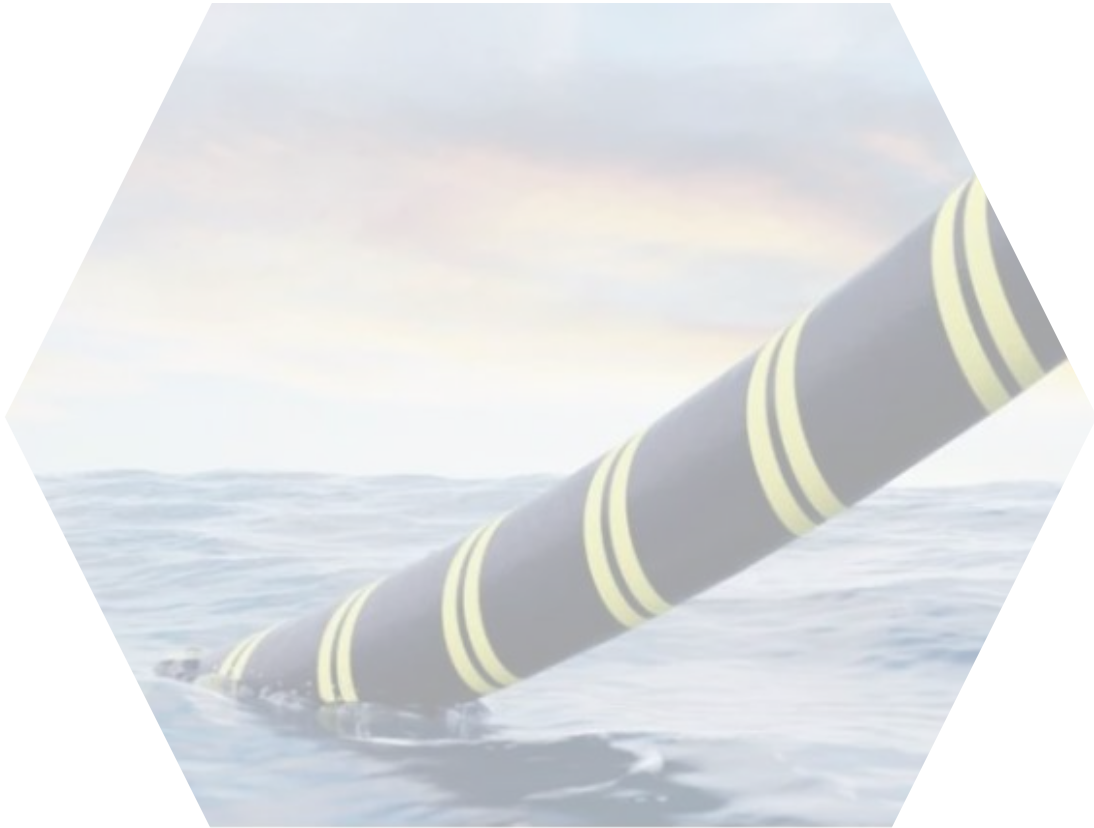




D3.4



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EXECUTIVE SUMMARY

This deliverable (D3.4 Specifications of the validation and test plans) outlines the comprehensive approach for validating and testing the Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), Partial Discharge (PD), and Vibration Monitoring Systems within the EasyDC-FOS project. The primary objective is to ensure that these advanced monitoring technologies meet the required performance standards and provide accurate, reliable data for the assessment and maintenance of HVAC and HVDC cable systems.

The validation process involves both laboratory and field trials, leveraging state-of-the-art methodologies and tools to achieve precise and actionable results. The plan outlines an overall framework for detailed procedures for laboratory tests, the setup of field trials, and the operational description of HVDC cable systems. However, the specific plans for lab and field test setup, testing, calibration, and validation are still in development and will be completed following the D3.4 Specifications of the validation and test plans. Key performance indicators (KPIs) are defined to evaluate the effectiveness of the monitoring systems, ensuring robust and reliable performance in both controlled and real-world environments.

This deliverable also addresses the challenges associated with calibration and validation in the field for the HVDC and HVAC field cable trials at the Danish and Norwegian TSO, Energinet and Statnett, respectively, ensuring that the monitoring systems are robust and reliable in diverse and dynamic environments.

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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
DAS	Distributed Acoustic Sensing
DTS	Distributed Temperature Sensing
PD	Partial Discharge
RTTR	Real Time Thermal Rating
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
RIA	Research and Innovation Action
KPI	Key Performance Indicator
XLPE	Cross-Linked Polyethylene
KTA	Key Type Assessment



1 INTRODUCTION

Overview of the validation & test plan: The Validation & Test Plan Specification outlines the comprehensive approach for validating and testing the Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), Partial Discharge (PD) and Vibration Monitoring Systems within the EasyDC-FOS project. This plan is designed to ensure that these advanced monitoring technologies meet the required performance standards and can provide accurate, reliable data for the assessment and maintenance of HVAC and HVDC cable systems. The validation process will involve both laboratory and field trials, leveraging state-of-the-art methodologies and tools to achieve precise and actionable results.

Objectives and Scope: The primary objective of this Validation & Test Plan is to demonstrate the effectiveness and reliability of the DTS, DAS, PD and Vibration monitoring systems in real-world conditions.

Specifically, the plan aims to:

1. Validate the performance of DTS and RTTR

- Assess the monitoring capabilities of fibre optic-based DTS integrated into long-distance corridors (>125 km).
- Utilize Real Time Thermal Rating (RTTR) algorithms, integrated into an Edge Infrastructure for real-time monitoring and immediate response.
- Test new generation DTS interrogator prototypes with algorithms for interrogator data processing, and Edge node data transfer with DTS, ensuring stability and accuracy under adverse conditions.

2. Validate the performance of DAS

- Evaluate the fault location and vibration monitoring capabilities of fibre optic-based DAS with an amplified sensing range (>125 km single-sided access).
- Test new generation and DAS interrogator prototypes with algorithms for interrogator data processing, and Edge node data transfer with and DAS, ensuring stability and accuracy under adverse conditions.

3. Validate the performance of vibration monitoring

- Evaluate the system's capability to identify unusual vibration patterns in critical components such as joints and terminations, which may indicate potential faults.
- Integrate the detection of cable sections with potential faults based on vibration anomalies into the Edge infrastructure, allowing the DAS to focus on the identified section of the cable and enhancing the fault localization algorithm

4. Validate the performance of PD monitoring

- Analyse the insulation ageing and early fault detection capabilities of fibre optic-based PD sensors with an amplified bandwidth range (order of GHz).
- Integrate the online PD monitoring system into a digital infrastructure, incorporating ageing prediction functionalities and real-time data processing.

The scope of this plan includes the detailed procedures for laboratory tests, the setup of field trials, and the operational description of HVDC and HVAC XLPE cable systems. It also outlines the key performance indicators (KPIs) to be used for evaluating the effectiveness of the monitoring systems, as well as the standards and guidelines to be followed. The plan addresses the challenges associated with calibration and validation in the field, ensuring that the monitoring systems are robust and reliable in both controlled and real-world environments.



2 Specification of Validation Plans

2.1 Laboratory Test Validation

2.1.1 Purpose of the Test Validation

The primary purpose of the laboratory tests is to validate the performance, stability, and accuracy of the DTS, DAS, PD, and vibration monitoring systems under controlled conditions. These tests aim to ensure that the technologies meet the required specifications and can reliably monitor and detect faults in HVDC cable systems over long distances. The laboratory environment allows for precise control of variables and conditions, facilitating the identification and resolution of potential issues before field deployment.

In addition to individual validation, the laboratory tests serve as a critical step to integrate all monitoring systems (DTS, DAS, PD and vibration interrogators with the edge) into a rack group. This integration ensures that the systems work cohesively as a complete monitoring unit. By testing the fully assembled and operational rack in the laboratory, potential issues with hardware compatibility, data synchronization, or software integration can be identified and resolved before field deployment.

2.1.2 Overall Test Procedures

2.1.2.1 Setup and Calibration

- Install DTS, DAS, PD and vibration monitoring systems in a controlled laboratory environment.
- Calibrate the sensors and interrogators to ensure accurate measurements.
- Configure the data acquisition systems and integrate them with the Edge Infrastructure for real-time data processing.

2.1.2.2 Thermal Testing (DTS & RTTR)

- Simulate varying thermal conditions along the HVDC/AC cable to assess the DTS system's ability to monitor temperature changes.
- Record temperature data and validate the accuracy of thermal capacity predictions.
- Use temperature reference measurements, e.g. PT1000 sensors, to validate the DTS readings and algorithm predictions
- Record temperature data and validate the accuracy of RTTR algorithms.
- Evaluate the system's response time and stability under different thermal loads.

2.1.2.3 Acoustic Testing (DAS)

- Generate controlled acoustic and vibration signals along the HVDC cable to test the DAS system's fault location and vibration monitoring capabilities.
- Measure the sensing range and accuracy of the DAS system, ensuring it meets the >125 km single-sided access requirement.
- Validate the algorithms for data processing and fault localization under simulated cable fault conditions.

2.1.2.4 Vibration Testing

- Generate controlled vibration signals along an HVDC/AC cable to test the vibration sensor's ability to detect anomalous vibrations between joints or terminations.
- Validate the anomaly detection algorithm to identify and localize the section of the cable with potential faults based on vibration patterns.

2.1.2.5 PD Testing

- Introduce controlled partial discharge events to evaluate the PD monitoring system's sensitivity and accuracy.
- Measure the system's ability to detect and analyse PD pulses, including the ageing prediction functionalities.
- Assess the system's performance in terms of frequency range, sensitivity, and false positive rate.

2.1.3 Key Performance Indicators (KPIs)

2.1.3.1 Sensors (hardware)

2.1.3.1.1 DTS

- Sensing distance > 125 km¹ with
 - < 10m spatial resolution.
 - < 20 min measurement time

¹ using G.654 ULL fibres

- < 2°C temperature resolution
- Response time and stability under varying thermal loads.

2.1.3.1.2 DAS

- Sensing distance > 125 km^{iError! Marcador no definido.} with
 - < 20 m spatial resolution (gauge length)
- Acoustic bandwidth 0 to 390 Hz

2.1.3.1.3 Vibration Sensor

- Vibration detection range from 0 to 5kHz.

2.1.3.1.4 PD Sensor

- Frequencies up to 1 GHz.
- Sensitivity <10 pC.
- PD pulse's location error <1%.
- False positive risk <10%.

2.1.3.2 Software (algorithms)

2.1.3.2.1 Fault Localization Targets

- Validate fault location accuracy within 10–20 m using early-stage algorithms, with a focus on gathering test data and insights for further refinement.
- Use data from DAS and point vibration sensors to assess initial algorithm performance, identifying strengths and areas for improvement.
- Evaluate fault localization time, aiming for below 30 minutes, while tracking progress against KPI targets and deriving improvement measures.
- Validate sensor (interrogator) performance independently of algorithms to establish baseline accuracy and system capabilities.
- Compare algorithm performance at different test stages with KPI targets, using results to iteratively enhance final algorithm development.

2.1.3.2.2 RTTR Algorithms Targets



- Algorithm accuracy compared to stationary and transient FEM simulations.
- Conductor temperature accuracy -2 to +4°C.
- Steady state ampacity $\pm 5\%$.
- Transient ratings: predicted conductor temperature accuracy -2 to +4°C (up to 1 week, continuous load).

2.1.4 Overall Evaluation Criteria

- Accuracy
 - The monitoring systems must provide precise measurements and fault localization within the specified KPIs.
- Reliability
 - The systems should demonstrate consistent performance under simulated cable fault conditions, including adverse environmental stresses.
- Response Time
 - The systems must respond promptly to changes in thermal, acoustic, and PD conditions.
- Stability
 - The systems should maintain stable operation without significant drift or errors over time.

2.1.5 Detailed Test Procedures

2.1.5.1 Lumiker High Current Test: Partial Discharge (PD) and Vibration Monitoring

2.1.5.1.1 Overall Identifiers

- Location
 - Lumiker test-bench, Bilbao.
- Timeline
 - Pending confirmation (around month 22, before end of T6.2 (M24) and T6.5 (M28)).
- Cable Type

- HVAC cable up to 55 kV.

2.1.5.1.2 Test Purpose

- Integration
 - Integrate vibration interrogator and DAS with the Edge to test fault localization functionality.
 - Integrate temperature interrogators (DTS and LTS) with the Edge to advance thermal modelling.
 - Establish communication between the PD interrogator developed by Lumiker and the PD analyser by Ampacimon, verifying data transfer to the Edge.
- Initial Validation
 - Verify the sensitivity (<10 pC) and frequency range (up to 1 GHz) of the PD system.
 - Confirm that AMP PD Analyzer can be interfaced with LMK PD interrogator using the edge to change the sensors pair to be interrogated.
 - Assess the ability of vibration sensors to detect and locate anomalies.
 - Confirm that all system data is correctly integrated into the Edge.
 - Preparation for Future Tests
- Provide a functional baseline to validate precision and sensitivity in more demanding environments (Nexans facilities).

2.1.5.1.3 Setup

- Equipment
 - Sensors
 - Vibration sensors (LMK).
 - PD sensors (LMK).
 - Local Temperature sensors (LMK).
 - Interrogators and Analysers
 - PD interrogator (LMK). (Estimated 3-4U).



- Vibration interrogator (LMK). (Estimated 3-4U).
- Local temperature interrogator LTS (LMK). (3U).
- DAS & DTS system (APS): total estimated rack space up to 13U. Comprising DAS, DTS, Amplifier, NAS, optional 1U PC or laptop for remote connection.
- PD analyzer (AMP). (Estimated rack space e.g., 23U-4U)).
- Edge Infrastructure: Provided by Barbara (BAR). (Estimated; 1-2U), standard power supply 220 Vac.

2.1.5.1.4 System Integration

- Proposed modular rack
- Each partner prepares and ships their equipment pre-installed in individual racks.
- The racks are designed to be modular and interoperable when combined at the deployment site, allowing a plug-and-play configuration. This results in the following advantages:
 - Time Efficiency
 - Reduces setup time during the test, as the equipment arrives pre-integrated.
 - Risk Mitigation
 - Minimizes delays caused by unforeseen assembly issues at Lumiker.
 - Simplicity
 - Easier troubleshooting since each rack retains its original communication.
- Implementation
 - Partners will coordinate to ensure compatibility between racks, including communication protocols, cabling, and power supply.
 - Pre-tests of individual racks will confirm that they meet the modular and integration requirements.

2.1.5.1.5 Test Procedure

- Initial Configuration



- Calibrate sensors and interrogators to ensure accurate measurements.
 - Install all systems in the modular rack and connect to the Edge.
- Partial Discharge Tests
 - Generate controlled PD events using dedicated generators.
 - Measure sensitivity and precision of the PD system across different pC levels.
- Vibration Tests
 - Simulate vibration signals by creating small, short circuits or with a surge generator.
 - Compare time delays between vibration sensors to locate anomalies.
- Integration Validation
 - Ensure PD, vibration, and temperature readings are correctly transferred to the Edge.

2.1.5.1.6 KPIs

- Detect vibrations in the range from 0 to 5kHz
 - Integration to Edge.
- All interrogators (PD, DAS, DTS, LTS, vibration sensors) must successfully transmit data to the Edge.
- Real-time visualization and processing of all sensor inputs to validate Edge functionality.

2.1.5.1.7 Responsible Parties

- Test lead
 - LMK.
- Data integration
 - BAR.
- Rack acquisition
 - Modular (each participant provides their own equipment, already integrated into small racks).
- Test collaborators

- LMK, APS, AMP and BAR.

2.1.6 AMP External Laboratory Test: PD System Validation

2.1.6.1 Overall Identifiers

- Location.
- Specialized HV Laboratory and Ampacimon facilities.
- Timeline.
- Within task ST6.5.1.

2.1.6.2 Test Purpose

- Validate the integration of the PD interrogator developed by Lumiker with AMP's PD analysers.
- Validate the PD acquisition system meets the expected requirements:
 - Sensitivity < 10pC
 - Frequency up to 1GHz.
- Validate that PD processing meets expected requirements:
 - Detection of PD pulses in noisy environment ($S/N \leq 1/50$).
 - PD pulse's location error <1%.
 - False positive risk < 10%.

2.1.6.3 Test Procedure

The detailed test procedure is to be develop as part of ST6.5.1, being part of deliverable D6.8. However, main parts of the test are described below.

- PD sensor will be installed in with long cables (~1km).
- Different type of PD pulses will be injected to the system in several environment scenarios (noise level, location, etc).
- Measurements and result provided by the PD system under test will be compared to the controlled values injected in the test setup.

2.1.6.4 KPIs

- PD System
 - Sensitivity of <10 pC.
 - Frequency range up to 1 GHz.
 - Detection of PD pulses mixed with noise ($S/N \leq 1/50$).
 - Error in PD pulse location <1%.
 - PD classification false positive >90%.

2.1.6.4.1 Responsible Parties

- Test Lead
 - AMPRack.
- Acquisition
 - Modular (each participant provides their own equipment, already integrated into small racks).
- Test Collaborators
 - AMP, LMK.

2.1.7 Nexans Laboratory High Voltage Test: Complete system validation in HVDC

Schematic of the installation should be installed by NEX

- Location
 - To be announced.
- Timeline
 - Pending confirmation (around month 26).
- Cable Type
 - HVDC cable prototype developed in the project.
- Test Purpose

- To be announced.
- Integration and validation of Fibre optic monitoring system before field tests:
 - Validate the performance of fibre-optic-based PD sensors (LMK) under HVDC conditions.
 - Assess the DTS and DAS systems (APS) for real-time thermal and vibration monitoring.
 - Verify the proper operation of the PD interrogator (LMK) when connected to the HVDC system.
 - Ensure real-time data transfer to the Edge infrastructure (Barbara) for advanced processing and predictive analysis.
- Validation of Predictive Models and Algorithms.
 - Fault Location Algorithm (KTA5)
 - Test an enhanced fault localization algorithm for long HVDC cables.
 - Use combined data from DAS and LMK vibration sensors to accurately pinpoint faults.
 - Real Time Thermal Rating Algorithm (RTTR) (KTA4)
 - Evaluate a predictive thermal management model to estimate cable operational capacity under different load and temperature conditions.
 - Validate multi-physics thermal models to predict temperature profiles and critical points.
 - Ageing Prediction Algorithm (KTA3)
 - Validate an ageing prediction model based on space charge accumulation in the cable insulation.
 - Use PD sensor data and electrical measurements to correlate PD activity with insulation degradation.
 - Real-Time Edge Processing and AI-Based Monitoring (KTA8)
 - Test the implementation of Machine Learning models in the Edge, enabling real-time cable health assessment.

- Preparation for Future Tests
 - Verify and validate the system's performance before deployment in the two field.
- Setup
 - Equipment
 - Fiber-optic Monitoring Systems.
 - DTS system (APS).
 - DAS System (APS).
 - Vibration Sensors (LMK).
 - Vibrator Interrogator (LMK).
 - PD Interrogator (LMK).
 - Edge Infrastructure (Barbara).
 - HVDC Test Environment
 - HVDC Cable Prototype developed in the project.
 - HV Laboratory at Nexans with controlled test conditions.
 - Space Charge Measurement System for Insulation Diagnostics.
 - System Integration
 - HVDC Test Cabinet for Nexans and Field Deployment.
 - A fully integrated cabinet will be assembled to house all monitoring systems for the Nexans test.
 - This same cabinet will later be deployed in the Energinet HVDC field test.
 - Procurement and Assembly Plan
 - The purchase of two cabinets is proposed—one for Energinet (HVDC) and one for Statnett (HVAC).
 - Companies with expertise in system integration into cabinets, such as APS and LMK, will be responsible for acquiring and assembling the cabinets.



- All required equipment will be installed and connected within each cabinet before deployment.
 - Pending Definition
 - Final confirmation of the procurement and integration approach is still to be defined.
 - Coordination between partners will be required to ensure compatibility of communication protocols, cabling, and power supply.
- Test Procedure:
 - Initial Configuration
 - Install and calibrate fibre-optic PD, DTS, DAS, and vibration sensors.
 - Connect all interrogators and data acquisition units to the Edge.
 - Verify communication between Edge and sensors before applying HVDC.
 - Partial Discharge Sensor Validation
 - Apply HVDC stress to the cable and measure PD activity.
 - Assess PD sensor sensitivity in detecting early-stage insulation faults.
 - Vibration Monitoring for Fault Localization
 - Use LMK vibration sensors to detect pressure waves generated by faults in the cable.
 - Synchronize DAS and vibration sensor data to determine fault locations.
 - Validate the fault location algorithm using real-time data.
 - Thermal Monitoring and Predictive Models Validation
 - Use DTS to track temperature variations along the cable during HVDC operation.



- Compare predicted vs. real temperature profiles using the Thermal Rating Algorithm.
 - Assess space charge accumulation effects on insulation degradation.
- Edge Data Processing Validation
 - Ensure PD, thermal, vibration, and space charge data are correctly synchronized.
 - Assess latency in data transmission from sensors to Edge.
 - Test real-time visualization and analytics on the Edge platform.
- KPIs
 - Predictive Model Accuracy
 - Fault location precision: within 10-20 meters.
 - Thermal model accuracy: conductor temperature deviation $\pm 2^{\circ}\text{C}$, ampacity deviation $\pm 2\%$.
 - Ageing model reliability: correlation of $>90\%$ with insulation degradation indicators.
 - Edge Integration
 - Stable real-time processing with no data loss.
- Responsible Parties
 - Test Lead
 - NEX.
 - Data Integration
 - BAR.
 - Rack Acquisition



- Pending confirmation.
- Test Collaborators
 - NEX, LMK, APS, BAR.



2.2 Field Test Validation

The primary purpose of the field tests is to validate the performance, stability, and accuracy of the DTS, DAS, PD, and vibration monitoring systems under real-world conditions. These tests aim to ensure that the technologies can reliably monitor and detect faults in HVDC cable systems over long distances in diverse and dynamic environments. The field environment presents a range of variables and conditions that are not present in the laboratory, providing a comprehensive assessment of the systems' robustness and effectiveness before full-scale deployment.

Specifically, the field tests will be conducted at two primary locations:

1. Øygarden 2 Project in Norway: This project focuses on validating health monitoring and fault location techniques in an AC underground cable system. The targeted section is the XLPE 420-kV cable connecting Solsvik and Kollsnes. The field trials will take place in Øygarden municipality, close to critical infrastructures such as Oil & Gas offshore fields, carbon capture and storage projects, a 1GW offshore wind park, and a Hydrogen factory.
2. COBRACable Project between Denmark and the Netherlands: This project aims to demonstrate condition monitoring methods in HVDC underground and submarine transition joints and a HVDC Cable End Termination in EDR Substation. The targeted section includes the submarine transition joint on the east side of Fanø island and a HVDC Cable End Termination in EDR Substation. The cable type is a 320-kV, bi-pole HVDC XLPE combined underground and submarine cable system.

These projects will provide valuable insights into the performance of the monitoring systems in different environments and cable types, ensuring their reliability and effectiveness before full-scale deployment.

2.2.1 Use Case I, Øygarden 2 project (STAT)

2.2.1.1 Key Performance Indicators (KPIs)

Fibres: Parallel to the three phases and strapped to phases at selected points.

- Fault Location Accuracy (validated via simulated disturbances)
 - Identify fault locations within ≤ 20 m, validated using simulated mechanical disturbances (e.g., controlled vibrations, external impacts) and induced thermal anomalies along the cable route.
- Fault Detection and Response Time (tested via simulated fault conditions)

- Detect and localize simulated anomalies (e.g., induced heating, vibration sources, artificial PD signals) within ≤ 30 minutes, ensuring real-time response capability.
- Thermal Monitoring with DTS (validated through induced heating scenarios)
 - Detect conductor temperature variations with -2 to $+4^{\circ}\text{C}$ accuracy, tested using controlled heating elements applied externally at select points.
 - Validate steady-state ampacity with $\pm 5\%$ accuracy, using simulated load variations to replicate operational changes.
- Fault Detection, Reliability and Robustness (validated through long-term monitoring and simulated disturbances)
 - Assess system robustness against varying environmental conditions through long-term measurements in both land and submarine sections.
 - Use simulated mechanical disturbances to ensure they do not trigger false alarms, validating system reliability in differentiating operational and non-operational events.
- Partial Discharge (PD) Detection (tested with artificial PD sources)
 - Detect and locate simulated PD pulses with an error margin of $\leq 1\%$, using calibrated PD sources injected at select cable joints or terminations.
 - Maintain false positive rate $< 10\%$, ensuring differentiation between background noise and actual discharge events.
- System Integration and Reliability
 - Ensure data transmission reliability of $\geq 95\%$ to SCADA and monitoring platforms, tested by introducing network disruptions and verifying system recovery time.
 - Assess system stability under varying weather conditions, including temperature and humidity changes over extended periods.

2.2.1.2 HVAC Operational Characteristics and Relevance to Validation

2.2.1.2.1 Thermal Behaviour

The HVAC cable systems at Øygarden is carrying fluctuating loads and is operated based on a n-1 principle which ensures that the system can continue to operate even if one component (such as a transformer or transmission line) fails.

- Relevance to Sensor Validation
 - DTS
 - Ensure accurate hotspot detection, particularly near joints, terminations, or under transient overload conditions.

2.2.1.2.1 *Electrical Stress and Partial Discharge*

The Øygarden cable systems consists of 420kV components (Cable and accessories).

During the first years of operation, the cable system will be operated at 300kV which will influence the electric field.

- Relevance to Sensor Validation
 - PD sensor
 - Validate the detection of low-magnitude PD events over long distances, accounting for noise filtering to address challenges posed by switching harmonics.

2.2.1.2.2 *Field Acoustic and Mechanical Effects*

HVAC cables are subject to alternating magnetic fields, which can induce mechanical vibrations. These oscillations can be influenced by factors such as cable tension and environmental conditions. In addition to this, the Øygarden cable system is installed across four islands, connected by bridges. The cables are installed inside these bridges, causing various acoustic noises.

- Relevance to Sensor Validation
 - DAS
 - Test sensitivity to acoustic events such as arcing or external impacts, ensuring minimal false positives during normal operations.
 - Vibration Sensor
 - Enhance the fault location, including the vibration sensor point that improves fault localization accuracy.

2.2.1.3 *Equipment and Instrumentation*

- DTS
 - For RTTR and monitoring of cable insulation.

- DAS
 - For fault location and vibration monitoring.
- Point Vibration Sensor.
- PD Analyzer
 - For insulation ageing analysis and early fault detection.
- Cross Bonding Cable Joint Locations
 - Approximately 14 joint bays available for monitoring. In addition to that, both termination stations are available for monitoring.

2.2.1.4 Site Access

- Ensure the site is prepared for the installation of monitoring equipment, including necessary civil works and safety measures.
- Access to XB boxes inside the maintenance hole.
- Access to the lower part of one end-termination at the substations.

2.2.2 Use case II, COBRACable project (ENER)

2.2.2.1 Key Performance Indicators (KPIs)

Fibers: Parallel to the two pole conductors on land, bundled to the pole pair in the seabed.

- Fault Location Accuracy (validated using simulated disturbances)
 - Identify fault locations within ≤ 20 m using simulated mechanical disturbances (e.g., controlled vibrations, external impacts) and induced thermal anomalies.
 - Validate fault detection capability by introducing controlled disturbances at accessible locations, including the transition joint.
- Fault Detection and Response Time (tested via simulated fault conditions)
 - Detect and Localize Simulated Anomalies (e.g., induced heating, vibration sources, artificial PD signals) within ≤ 30 minutes, ensuring real-time monitoring capability.
 - Assess Response Time for Different Fiber Placements (parallel to land cables, bundled with submarine cables) to evaluate sensor performance under varying installation conditions.
- Thermal Monitoring with DTS (validated through induced heating scenarios)
 - Detect temperature variations with -2 to $+4^{\circ}\text{C}$ accuracy, tested by applying controlled external heating at select land and submarine sections.
 - Identify thermal imbalances between pole conductors under simulated asymmetric loading conditions.
 - Verify DTS sensitivity in submarine conditions by monitoring temperature variations near the transition joint.
- Fault Detection Reliability and Robustness (validated through long-term monitoring and simulated disturbances)
 - Assess system robustness against varying environmental conditions through long-term measurements in both land and submarine sections.
 - Use simulated mechanical disturbances to ensure they do not trigger false alarms, validating system reliability in differentiating operational and non-operational events.



- Partial Discharge (PD) Detection (tested with artificial PD sources)
 - Detect and locate simulated PD pulses with an error margin of $\leq 1\%$, using calibrated PD sources at transition joints and land cable joints.
 - Maintain a False Positive Rate of $< 10\%$ to differentiate real PD activity from background noise.
- System Integration and Reliability
 - Ensure data transmission reliability of $\geq 95\%$ to SCADA and monitoring platforms, tested by introducing network disruptions and verifying system recovery time.
 - Validate continuous monitoring capabilities under varying environmental conditions, including temperature and humidity changes on land and seabed conditions in the submarine section.

2.2.2.2 HVDC Operational Characteristics and Relevance to Validation

It is important to highlight these aspects for HVDC systems because their unique operational characteristics—such as steady-state DC current, unidirectional electric fields, and high-frequency noise from VSC switching—pose distinct challenges for monitoring equipment. Understanding these differences ensures accurate sensor validation and reliable performance in detecting faults, thermal anomalies, and partial discharge events specific to HVDC environments.

2.2.2.3 Voltage Source Converter Characteristics

VSC-based HVDC systems use fast-switching power electronics (e.g., IGBTs) for AC/DC conversion. This results in clean, controlled DC voltage but can introduce high frequency switching noise.

- Relevance to sensor validation
 - DTS
 - Validate temperature sensing accuracy in the presence of thermal gradients caused by dc current and localized heating at converter interfaces.
 - DAS
 - Confirm that acoustic signals from mechanical vibrations, such as those induced by converter switching or transient events, are distinguishable from background noise.

- PD Sensor
 - Verify the system's ability to detect partial discharge caused by high-frequency switching harmonics or converter-related electrical stresses.

2.2.2.3.1 *Thermal Behaviour*

HVDC cables carrying continuous constant DC current exhibit steady-state thermal profiles, with heat generation proportional to resistive losses in the conductor and insulation.

- Relevance to Sensor Validation
 - DTS
 - Ensure accurate hotspot detection, particularly near joints, terminations, or under transient overload conditions.

2.2.2.3.2 *Electrical Stress and Partial Discharge*

The insulation in HVDC cables experiences a steady unidirectional electric field with higher stress at terminations and joints.

- Relevance to Sensor Validation
 - PD Sensor
 - Validate the detection of low-magnitude PD events over long distances, accounting for noise filtering to address challenges posed by switching harmonics.

2.2.2.3.3 *Field Acoustic and Mechanical Effects*

Mechanical oscillations in HVDC cables are minimal due to the absence of alternating magnetic fields. Acoustic events, if any, are typically related to faults or external mechanical impacts.

- Relevance to Sensor Validation
 - DAS
 - Test sensitivity to acoustic events such as arcing or external impacts, ensuring minimal false positives during normal operations.

2.2.2.4 *Equipment and Instrumentation*

- DTS
 - For thermal rating of the HVDC cable system.



- DAS
 - For fault location and vibration monitoring.
- Point Vibration Sensor.
- PD Analyzer
 - For insulation ageing analysis and early fault detection at DC excitation.
- Transition Joint and Cable Termination
 - For monitoring and validation.

2.2.2.5 Site Access

- Access to premises within EDR substation where the rack(s) system(s) housing the DTS, DAS, PD, and vibration interrogators, etc., are to be installed.
- Access to bonding leads/cables and link box at one transition joint.
- Access to the lower part of one end-termination at EDR substation.

2.2.3 Safety and Compliance Considerations for both Use Cases

- Regulatory Compliance
 - Ensure all activities comply with relevant standards and regulations, including IEC62067 and CIGRE's TB852 for insulation properties.
- Safety Protocols
 - Implement safety protocols to protect personnel and equipment during installation and testing.
- Environmental Impact
 - Assess and mitigate any potential environmental impacts of the field trials.
- Emergency Procedures
 - Establish emergency procedures for handling any incidents that may occur during the trials.
- Laser Safety
 - Up to Class 3R



2.3 Relevant Standards and CIGRE Technical Brochures (TBs)

The following standards and CIGRE Technical Brochures (TBs) are relevant for the validation and testing of HVDC and HVAC cable systems.

- IEC 60287
 - Standards for calculating the current rating of cables.
- IEC 60853
 - Standards for calculating the cyclic and emergency current rating of cables.
- CIGRE TB 640
 - Guidelines for the thermal rating of cables.
- CIGRE TB 852
 - Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV.



3 Validation and Calibration in the Field

3.1 Challenges in Field Validation and Calibration

Field validation and calibration of the DTS, DAS, and PD measurement systems present several challenges:

- Lack of Fault Events
 - It is unlikely that the HVAC and HVDC cables, joints, terminations, and link boxes will experience any faults or abnormal thermal ratings during the field trials. Normal load cycles are expected, but no significant events may occur to test the systems' fault detection capabilities.
- Absence of PD Events
 - Similarly, it is hoped that there will be no partial discharge events in the cables, joints, terminations, and link boxes. This lack of events makes it difficult to validate the PD monitoring system's effectiveness in real-world conditions.
- Environmental Variability
 - Field conditions can vary significantly, making it challenging to maintain consistent calibration and validation standards.
- Accessibility
 - Some sections of the cable systems, especially submarine cables, may be difficult to access for calibration and validation purposes.

3.2 Strategies for Addressing Field Challenges

To address these challenges, the following strategies will be implemented:

- Simulated Fault Events
 - Introduce controlled fault events and thermal anomalies in a safe and controlled manner to test the monitoring systems' capabilities.
- Enhanced Calibration Techniques
 - Use advanced calibration techniques to ensure the accuracy and reliability of the monitoring systems, even in the absence of real fault events.
- Environmental Control

- Implement measures to control environmental variables as much as possible during the field trials.
- Remote Access and Monitoring
 - Utilize remote access and monitoring technologies to facilitate calibration and validation in hard-to-reach areas.

3.3 Calibration Procedures

Calibration is essential to ensure the accuracy and reliability of the measurement systems. Without proper calibration, validation cannot be effectively performed.

3.3.1 DTS Calibration Overview

- The measurement accuracy of the DTS interrogator is calibrated and verified in a factory acceptance test. A calibration is required for the sensor fibre in the cable to adjust temperature offsets and gradients to the sensor fibres properties.
- Independent Temperature Observations
 - DTS calibration requires independent temperature observations along parts of the fibre cable.
- Practical Calibration Challenges
 - Calibrating with single points rather than sections and with small temperature differences.

3.3.1.1 Calibration Methods and Techniques

- Coiled Cable Sections
 - Use coiled 10 m sections of cable and multiple collocated thermistors to calibrate and validate the DTS temperature signal. Collocated thermistors provide reference temperature measurements for direct comparison and correlation.
- Common Calibration Practices
 - Coiling fibre optic cable is common for calibration. Calibration with cable sections in a known temperature bath is recommended once deployed.
- Optimal Calibration Temperatures
 - Use two temperature set points: A colder bath for low temperatures (e.g. ice bath or colder ambient) and a warmer bath (usually ambient) for higher temperatures.

3.3.2 Calibration of PD measurement systems

- Importance of Calibration
 - Calibration is essential for determining the scale factor of a PD measuring system. It involves injecting a known charge across the terminals of the device under test using a traceable calibrator.

3.3.2.1 Reference Impulse Charge Generator and Calibration Procedure:

- Reference Impulse Charge Generator
 - A programmable reference impulse charge generator is a key tool for calibration.
 - It consists of an arbitrary waveform generator and a series capacitor, allowing for the injection of precise, known charges into the system.
- Calibration Products
 - Inject known charges across a wide range (e.g., 2.5 nC to 2 pC).
- Compared measured values to reference values and calculate measurement errors and linearity figures.

3.3.3 DAS Calibration and Calibration Methods and Techniques

- The measurement accuracy of the DAS interrogator is calibrated and verified in a factory acceptance test. A calibration to the sensor fibre in the cable is not required.
- Coiled Cable Sections (optional)
 - Use coiled 10 m sections of cable and multiple Contact Microphones (Piezoelectric Sensors) to calibrate and validate the DAS acoustic signal. Contact Microphones provide reference acoustic measurements for direct comparison and correlation.
- Common Calibration Practices
 - Calibration with cable sections in a known acoustic field is recommended once deployed.
- Optimal Calibration Conditions
 - Use controlled environments for low acoustic vibrations and ambient environments for higher acoustic vibrations, e.g., in or next to a server rack at the substation.

3.4 Detailed Calibration Procedures for Specific Equipment

3.4.1 Use Case I and Case II

3.4.1.1 DTS

- PT1000 Sensors.
- Battery-powered temperature loggers for time-dependent logging, e.g., daily temperature variations.
- Fibers at transition joint and end-termination can be accessed.

3.4.1.2 DAS and Vibration

- Sound Transducers
- Manual Tapping
 - Fibers at transition joint and end-termination can be accessed, including certain FO manhole locations alongside the land cable route.

3.4.1.3 PD

- Injection of PD pulses at bonding cables at transition joint.

3.5 Data Collection and Analysis

3.5.1 Data Collection

Collect data from the DTS, DAS, PD monitoring and vibration sensor systems continuously during the field trials. Ensure that data is accurately timestamped and stored securely.

3.5.2 Data Analysis

Analyse the collected data to identify any anomalies or patterns that may indicate faults or abnormal conditions. Use AI algorithms to assist in the analysis and interpretation of the data.

3.5.3 Reporting

Document the findings from the data analysis, including any detected faults or anomalies, and compare them to the expected performance metrics. Provide

detailed reports to stakeholders and use the insights gained to improve the monitoring systems.



4 Output for WP8

4.1 Expected Outcomes and Deliverables

WP8 aims to achieve the following outcomes and deliverables:

- Validated Edge Nodes
 - Two Edge Node pilots (Thermal Rating & Fault Location Edge Node and Insulation Ageing Edge Node) tested and validated in laboratory settings, ready for deployment in Use Cases (UCs).
- Integrated Monitoring Systems
 - Successful integration and deployment of DTS, DAS, PD monitoring, and vibration sensor systems in existing facilities of the end-users.
- Field Test Results
 - Comprehensive data from field tests, including continuous monitoring of health status and fault location detection over a 5-month period.
- Performance Analysis
 - Detailed performance analysis and evaluation of the monitoring systems based on predefined KPIs.
- Technology Development Roadmap
 - A roadmap outlining the steps required to scale up the cable system, modelling, and monitoring innovations towards new technological milestones and future commercialization.

4.2 Key Performance Indicators (KPIs): Summary and Quantification

4.2.1 Summary of KPIs

A *Summary of Key Performance Indicators* (KPIs) provides an overview of the most important metrics used to measure the performance and success of a project, team, or organization. This summary highlights the key metrics that are tracked to ensure goals are being met and to identify areas for improvement.

4.2.2 Quantification of KPIs

Quantification of KPIs involves assigning numerical values to the performance indicators. This process includes defining specific, measurable targets for each

KPI and tracking progress against these targets. Quantification allows for objective assessment and comparison over time, making it easier to evaluate performance and make data-driven decisions.

4.3 Integration with WP8 Activities

The activities in WP8 are closely integrated with the overall project objectives and other work packages, particularly WP3.

- Edge Nodes Testing and Pre-Use Case Verification (T8.1)
 - Ensure that the Edge Infrastructure complies with the requirements set out in WP3.
 - Conduct system testing and pre-validation activities in laboratory settings.
 - Prepare validated Edge Node pilots for deployment in UCs.
- Delivery and Installation in UCs (T8.2)
 - Package, transport, and deliver prototypes and systems to UC sites.
 - Configure and deploy the integrated Edge Infrastructure, including fibre splicing and sensor installation.
 - Implement a commissioning strategy for operation and monitoring.
- Field Test UCs (T8.3)
 - Apply testing, assessment, and monitoring protocols defined in T3.4.
 - Record and assess the behaviour of developed models, prototypes, and integrated infrastructure.
 - Demonstrate AC and DC monitoring edge nodes in real-world environments.
- UCs Assessment and Technology Development Roadmap (T8.4)
 - Evaluate UCs results and demonstration campaign data.
 - Report quantitative evaluation metrics and measurement methods.

- Establish the main pillars of the technology development roadmap for scaling up innovations.

4.4 Reporting and Documentation Requirements

To ensure transparency and accountability, the following reporting and documentation requirements will be adhered to:

- Regular Progress Reports
 - Submit regular progress reports detailing the activities, findings, and challenges encountered during the implementation of WP8.
- Data Collection and Analysis Reports
 - Document the data collection and analysis processes, including the methodologies used and the results obtained.
- Performance Evaluation Reports
 - Provide detailed reports on the performance evaluation of the monitoring systems based on the predefined KPIs.
- Final Project Report
 - Compile a comprehensive final project report summarizing the outcomes, deliverables, and lessons learned from WP8.
- Open Access Publications
 - Ensure immediate open access to all scientific publications related to relevant project results while maintaining IPR by the consortium.

4.5 How WP3 Feeds into WP8

WP3: Specification of Technical Innovations, Design & Monitoring of Hybrid HVDC Transmission Cables.

T3.1: Specification of Innovations in Cable Systems (Deliverable D3.1)

- Output
 - Detailed specifications for innovations in cable systems, including enhanced insulating materials and cable design parameters.

- Integration with WP8
 - These specifications will guide the development and testing of cable systems in WP8, ensuring that the innovations meet the required standards and performance metrics.

T3.2: Specification of Predictive Models for Cable System Ageing, Life & Reliability (Deliverable D3.2).

- Output
 - Predictive models for cable system ageing, life, and reliability, including AI methods and strategies for managing information from monitoring systems.
- Integration with WP8
 - These models will be used in WP8 to assess the ageing and reliability of cable systems during field tests, providing valuable data for performance analysis and future improvements.

T3.3: Specification of Enhanced Monitoring & Fault Location Systems Based on Fibre Optics (Deliverable D3.3).

- Output
 - Specifications for enhanced monitoring and fault location systems, including DTS, DAS, and PD technologies.
- Integration with WP8
 - These specifications will be used to develop and deploy the monitoring systems in WP8, ensuring accurate and reliable fault detection and condition monitoring in real-world environments.

T3.4: Validation & Test Plan Specification (Deliverable D3.4)

- Output
 - Comprehensive validation and test plans, including KPIs, testing protocols, and evaluation criteria.
- Integration with WP8
 - These plans will be applied in WP8 to validate the performance of the monitoring systems, ensuring that they meet the required standards and deliver accurate results.

5 Environmental and Safety Considerations

5.1 Environmental Impact Assessment

While the activities involved in the validation and testing of the DTS, DAS, and PD monitoring systems are not expected to cause harm to the environment, animals, or plants, it is essential to conduct a thorough environmental impact assessment to ensure all potential risks are identified and mitigated. Key considerations include:

- Substances and Processes
 - Ensure that no harmful substances or processes are used during the implementation of the activities or because of the outcomes.
 - In this case, only isopropanol during the fibre splicing works
- Protected Areas
 - Verify that the activities do not impact endangered fauna and flora or protected areas.
- Waste Management
 - Implement proper waste management practices to minimize environmental impact.
- Energy Consumption
 - Monitor and optimize energy consumption during testing and validation to reduce the carbon footprint.

The environmental impacts of the deployed cable system will be assessed during the demonstration to track performance and optimize sustainability. A refined set of indicators, selected from the Environmental Footprint impact assessment method (European Commission, 2025), will be used. These indicators are based on consensus-based scientific models for reliability.

Impact assessment will follow the ISO 14040 and ISO 14044 Life Cycle Assessment methodology, ensuring a comprehensive evaluation of the system's life cycle. The assessment will align with the methodology in D3.1 (Section 5.3), including scope-setting and indicator evaluation.

5.2 Safety Protocols and Risk Management

Safety is paramount, especially when dealing with high voltage systems and critical infrastructure. The following safety protocols and risk management strategies will be implemented:

5.2.1 High Voltage Safety

- **Øygarden 2 Project:** The validation will take place within High voltage substation and near a 420kV cable system installation.
- Safety measures will include:
 - Proper insulation and grounding of all equipment, if applicable
 - Use of personal protective equipment (PPE) for all personnel.
 - Regular safety drills and emergency response plans.
- **COBRACable Project:** The validation will take place within High voltage substation and in close proximity to a 320kV bipole HVDC XLPE combined underground and submarine cable system.
- Safety measures will include:
 - Strict adherence to high voltage safety standards.
 - Implementation of safety barriers and warning systems, if applicable (to be assessed)

5.2.2 General Safety Protocols

- Training
 - Ensure all personnel are adequately trained in high voltage safety and emergency procedures.
- Risk Assessment
- Conduct comprehensive risk assessments before starting any activities.
- Emergency Response
 - Develop and implement emergency response plans for potential incidents.
- Health Monitoring
 - Regular health checks for personnel working in high-risk environments.

5.3 Compliance with Regulatory Requirements

compliance with regulatory requirements is essential to ensure the safety and legality of the activities. Key considerations include the following sub-sections.

5.3.1 Regulatory Standards

- IEC62067 and CIGRE's TB852
 - Ensure all insulation properties and monitoring systems meet these standards.
- Local Regulations
 - Adhere to local regulations and obtain necessary permits for all activities.

5.3.2 Critical Infrastructure Protection

In Denmark, the Danish Business Authority (Erhvervsstyrelsen) defines critical infrastructure as: "Infrastructure, including facilities, systems, processes, networks, technologies, assets, and services necessary to maintain or restore essential societal functions." The COBRAcable (COpenhagen-BRussels-Amsterdam cable) is critical infrastructure electricity grids of Denmark and the Netherlands. The Danish energy sector, like the rest of Danish society, faces increasing threats from cyberspace. The latest threat assessment from the Center for Cyber Security (CFCS) states that the threat from cyber espionage and cybercrime remains very high, the highest threat level.

Current Access and Potential Challenges

As of January 16, 2025, it is relatively easy to access the converter station and set up the field trial.

However, if the threat landscape changes, physical access to the on-site converter station and measurement equipment for calibration, testing, and validation could become very restricted.

Recommendations

Consider remote control of all equipment, including restart, data transfer and backup, calibration (DTS, DAS, and PD), and reference measurements (including but not limited to temperature, sound, and PD).

Evaluate the need for Uninterruptible Power Supply (UPS) on measurement equipment to ensure data security and continuous measurements.

Assess the impact of power or internet connection loss on measurement systems. Determine if systems will restart and continue measuring when power is restored, and if data will be lost if remote control or internet connection is disrupted for minutes, hours, or days.

Physical Protection: Implement measures to protect critical infrastructure from physical threats, including unauthorized access and vandalism.

Cybersecurity: Ensure robust cybersecurity measures are in place to protect the monitoring systems and data from cyber threats.

Coordination with Authorities: Work closely with local authorities and stakeholders to ensure compliance with all regulatory requirements and to address any concerns related to critical infrastructure protection.

By implementing these environmental and safety considerations, the project will ensure the safe and responsible validation and testing of the DTS, DAS, and PD monitoring systems, while minimizing any potential risks to the environment, personnel, and critical infrastructure.



6 CONCLUSIONS

This report highlights the importance of thoroughly validating and testing the Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), Partial Discharge (PD), and Vibration Monitoring Systems. Key points include the roles of laboratory tests and field trials. Laboratory tests are performed in controlled environments to initially calibrate the systems and ensure they meet performance standards. These tests allow for adjustments and improvements before deploying the systems in actual use.

Field trials, on the other hand, are essential for evaluating the systems' effectiveness in real-world conditions, which can be unpredictable and challenging. These trials provide valuable insights into how well the technologies perform when faced with actual environmental and operational factors. By testing the systems in various conditions, such as different weather patterns and installation scenarios, field trials help confirm the reliability and accuracy of the monitoring data.

The validation process ensures that these advanced monitoring technologies can provide precise and dependable data, which is crucial for maintaining HVAC and HVDC cable systems. The deliverable also addresses challenges related to calibration and validation, making sure the systems are reliable and meet strict performance requirements.

Moving forward, the next steps involve continued collaboration between different departments to complete the project on time and achieve the desired results. This teamwork is essential for overcoming potential obstacles and ensuring that the project goals are met. By integrating feedback and expertise from various teams, the project will successfully implement and validate the monitoring systems, ultimately enhancing the safety and reliability of HVAC and HVDC cable systems.



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8 APPENDIX A: Specifications of the Validation and Test Plans for COBRACable Field Trial Setup

The detailed descriptions of the field trial setup at COBRACable are in a separate internal document, as they contain sensitive information about critical infrastructure. This document will eventually be made "public."



9 APPENDIX B: Specifications of the Validation and Test Plans for Øygarden 2 Field Trial Setup

The detailed descriptions of the field trial setup at Øygarden 2 are in a separate internal document, as they contain sensitive information about critical infrastructure. This document will eventually be made "public."

