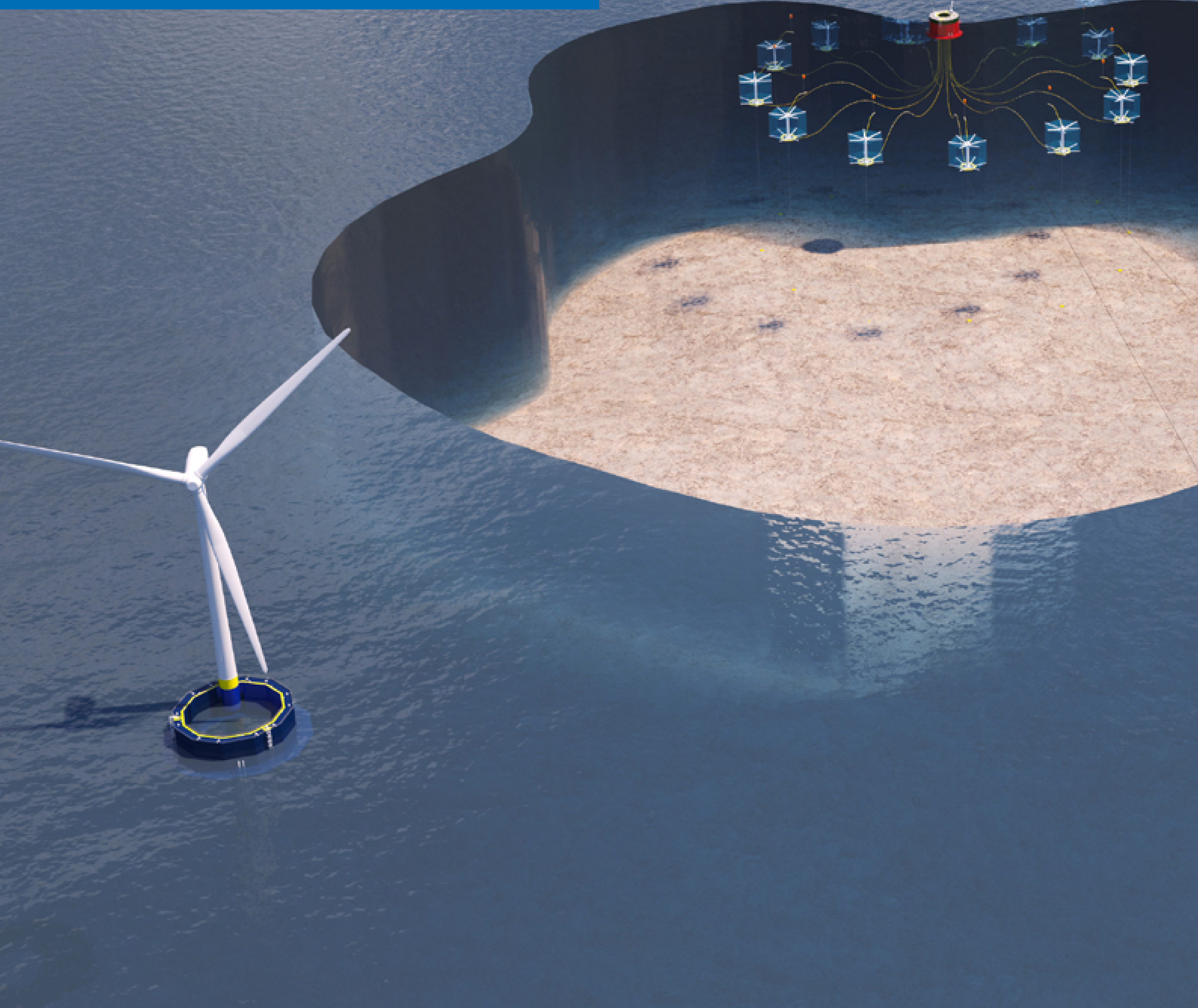
Nordic Innovation

Co-locating Floating Wind and Aquaculture: Lessons from the Nordic OFFWOFF Project

Freja Offshore, SubFarm, DHI, ÅKP, Fyrbodal's Association of Local Authorities



Disclaimer

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Executive Summary

Through the **OFFWOFF (Offshore Floating Wind and Offshore Fish Farming)** project, we have explored the possibility of coexisting offshore wind and marine aquaculture within the same marine space. This highlights the potential for multi-functional solutions where various societal interests can coexist and reinforce one another. Funded by Nordic Innovation, the project brings together Nordic expertise from across disciplines to assess opportunities for smarter and more sustainable use of the ocean.

The work has been structured across five work packages, each with defined objectives and deliverables that all feed into the concept of co-locating wind and fish farms. Supporting reports, included as attachments to this report, provide detailed analysis on metocean conditions, hydrodynamic performance, underwater noise, feasibility of coexistence and business potential.

The results show that floating wind turbines and submerged fish farms can operate side by side, with minimal interference between mooring systems or operations. The only impact to the wind farm is a requirement of three mooring lines on the mooring group facing away from the SubFarm to allow for a 2-line mooing failure scenario. The innovative SubFarm system enables dynamic cage submersion to optimise biological conditions, minimising exposure to storms, predators, and sea lice. Biological data from Mareld indicate favourable conditions for salmon farming, though further in situ monitoring is needed to improve current data quality and confirm long-term feasibility.

Underwater noise modelling confirms that operational noise from both wind and fish farms contributes only to small local acoustic footprints around every turbine and fish farm, leading to no significant impact on the farmed fish and protected marine species during operation. With noise mitigation measures in place during installation works, such as pile driving (if needed), the impact on farmed fish and protected marine species can be heavily reduced.

OFFWOFF finds a robust business case for offshore aquaculture. With an estimated CAPEX of NOK 4.7 billion, the co-located project could deliver (pre-tax):

- Annual net cash flow: NOK 1.8 billion
- Net present value (NPV): NOK 4.2 billion
- Internal rate of return (IRR): 19%
- Payback time: 9 years

Using Rogaland in Norway as a benchmark, the Swedish west coast could achieve SEK 2.4–2.8 billion in annual value creation and generate up to 2,000 new jobs. Co-location enhances regional food security by enabling local salmon production in volumes ten times larger than current national consumption, reducing Sweden's dependence on imports.

The OFFWOFF project demonstrates that Sweden—and the wider Nordic region—can lead the world in sustainable and efficient marine space use. Using the Mareld project in Skagerrak as the pilot case, the project confirms that co-production of renewable energy and farmed Atlantic salmon is **technically feasible, biologically viable, and economically attractive**. Mareld and the OFFWOFF concept acts like a blueprint for future projects across the Nordic seas. As spatial pressure on marine areas increases, co-location offers a forward-looking solution that aligns with EU and Nordic policy goals for climate, food, and economic resilience. With the right regulatory support, stakeholder engagement, and continued innovation, the OFFWOFF concept is ready to be scaled and replicated, positioning the Nordic region as the frontrunner of sustainable ocean use.

Introduction

Background of the OFFWOFF co-location project

Offshore Wind has been identified as one of the key solutions in the short and medium term to meet the need for new renewable energy. Wind installations have increased in the last decade in Scandinavia. Sweden leads the way, with over 12 GW of installed capacity and 27 TWh of electricity produced in 2021. In Denmark, wind energy has taken on a leading role in powering the country, accounting for half of the electricity produced. The Norwegian government has allocated areas for 30 GW of offshore wind capacity by 2040. These development plans challenge the utilisation of the sea areas where access is already under pressure from, for instance, increased maritime traffic. This enforces the need for a significant co-location of various forms of sea-based Industries to enable a sustainable use of the seas.

Similarly, aquaculture farming activities are moving out into the open sea, also increasing the need to optimise the use of marine areas. As the global population continues to grow, the demand for sustainable food becomes increasingly critical, and the oceans hold the key to increasing the supply of healthy proteins. With wild catch reaching stagnation, the growth must now come from aquaculture. However, conventional near-shore fish farming faces challenges, including limited space for expansion, high fish mortality and welfare concerns, and remote locations that contribute to long supply chains and increased carbon emissions.

To address these limitations, offshore fish farming emerges as a promising alternative for expansion. It solves many of the user conflicts arising in near-shore areas, and the water quality in the open ocean is more favourable for the fish health, thus resulting in better fish welfare and the nutrients from the farms are spread over larger areas due to sea currents, avoiding negative effects, as can be seen in some fjords with poor water exchange.

SubFarm AS has developed a single-point moored submersible fish farming cage for use in harsh environments offshore. The cages are deployed in groups and individually connected to a central feed platform via an umbilical. Each cage is equipped with cameras, sensors and air domes. The cages are freely positioned in the water column, allowing vertical movement to adapt to sea conditions. This ensures optimal growing conditions, promoting excellent fish welfare and health. During sampling and harvesting, a winch-operated roof is lowered to crowd the fish, which are then evacuated to a surface boat via a flexible hose.

Freja Offshore AB has applied for a permit to build, operate, and decommission the Mareld wind farm located in the Skagerrak in the Swedish Economic Zone (SEZ), approximately 40 km west of Lysekil on the mainland of the Swedish coast. This wind farm will utilise the innovative floating platform concept, which enhances the performance and sustainability of wind farms, as it allows installation in deeper waters than for bottom-fixed platforms. Developing offshore wind power in Sweden is not only about generating renewable electricity – it is also an opportunity to shape the sustainable use of our seas for the future. By integrating ecological considerations, long-term economic value, social engagement, and technological innovation, offshore wind projects can contribute to a transformation that is both sustainable and inclusive.

Combining these two initiatives provides a unique opportunity to explore synergies and resolve challenges linked to the co-location of offshore submerged fish farms and floating wind farms, which is why the OFFWOFF project was established. Sharing marine space in this way enables more efficient use of the sea while creating positive synergies. Co-location can also strengthen the economic viability of projects through diversified value streams, increased resilience, and greater acceptance among neighbouring communities. Other possible benefits are local value creation through employment, service partnerships, and regional innovation.

Collaboration between sectors also opens doors for shared logistics, technical infrastructure, and environmental monitoring. It supports innovation and research, fosters operational efficiency, and helps reduce the environmental footprint of marine operations. The result is a stronger, more adaptive marine use model that benefits all parties involved.

The OFFWOFF study has focused mainly on addressing environmental concerns linked to the co-existence of the two activities, such as those linked to the biological impact of underwater noise and mooring system interference, and aimed to develop coherent business plans. To achieve that, other project partners, such as DHI, ÅKP and Fyrbodal's Association of Local Authorities, have also participated and contributed to the studies and the results of the project. The study has been partly funded by Nordic Innovation.

The project participants

The OFFWOFF project has been carried out by a consortium built upon a strong partnership covering cross-sectoral interests such as business, innovation, and societal development. The consortium possesses complementary strengths, ensuring delivery upon sustainability, entrepreneurship, and competitiveness in the Nordic ocean economy. The consortium comprises Freja Offshore (Sweden), SubFarm (Norway), DHI (Denmark) ÅKP (Norway) and Fyrbodal's Association of Local Authorities (Sweden), with Freja Offshore as the Consortium Lead.

Freja Offshore

Freja Offshore AB is a Swedish company dedicated to sustainably develop, build, and operate offshore floating wind farms in Sweden. Freja is a 50-50 joint venture between the Swedish company Hexicon AB and Mainstream Renewable Power (mainly owned by the Norwegian company Aker). Together, they bring unique capabilities and experiences: Stockholm-based Hexicon contributes global project-development experience, having advanced floating-wind initiatives in markets from South Korea to Scotland, with joint-venture partners bringing in-country know-how on permitting, regulations and local

Freja Offshore

supply chains for each specific country. While Mainstream (Aker) leverages learnings and knowledge from five decades of planning, designing, and executing offshore projects in the North Sea and elsewhere globally. The company has core expertise in project planning and execution methodology, technology know-how, and fabrication competencies to scale and industrialize offshore wind in a sustainable way. Freja believe that renewable energy solutions should not be limited to one technology. That is why we take a tech-agnostic stance on floating offshore wind power technology. We are always surveying the market and research field for the most suitable technology for each of our unique project sites. Our ambition is not only to use the most well-known or popular technology but the one that best suits the project's specific conditions. In addition to this, we are committed to exploring other sustainable activities that could co-exist within and with the wind farm. Since our project is in the early stages of development, now is the perfect time to start planning, to be able to create renewable energy solutions for the future with an open and explorative mindset.

SubFarm

SubFarm is a technology development company in the aquaculture industry, part of the Open Ocean Holding group, which includes Open Ocean Farming, an internationally focused fish farming company. Subfarm's objective is to redefine the standards for open ocean aquaculture, prioritising fish welfare and sustainability.

The core of Subfarm's technology is a single-point moored, winch-operated, submerged fish cage. This innovative design ensures optimal temperature and conditions for salmon, protecting them from sea lice and toxic algae. The technology allows for efficient operations in rough weather conditions and facilitates easy disconnection for onshore maintenance.

Subfarm's technology addresses the current challenges in salmon farming. With limited sustainable fjords available, Subfarm's technology enables fish farming on a global scale. It mitigates the lice problem and visual pollution by submerging the farm, thus minimising surface footprint. By establishing production close to consumer markets, Subfarm aims to reduce the environmental impact of salmon transportation.

The applications of Subfarm's technology are diverse, ranging from existing farms and exposed areas to the open ocean. It significantly reduces the risk of biomass loss and is ideally suited for co-location within offshore wind farm perimeters, promoting efficient use of ocean space. The Subfarm team comprises the three founders, Karl Christian Strømsem, Morten Lyssand and Paal Hylin, along with Scientific Advisor Brit Hjeltnes (former director of the Norwegian Veterinary Institute). With the addition of three active shareholders, all successful entrepreneurs and owners of cornerstone companies in the marine and offshore energy industries, the team brings together a wealth of experience from the fish farming, energy and marine industries. Their collective expertise propels Subfarm's mission to revolutionise fish farming, making it more sustainable and efficient.

DHI

DHI is an independent and research-based institute providing specialist consultancy services focusing on water environments, established in Denmark. The ultimate owner of DHI A/S and its subsidiaries is the DHI

Foundation, which is a not-for-profit foundation based in Denmark. DHI is one of seven Danish GTS institutes (RTO) recognised by the Danish Ministry of Higher Education and Science for its role in advancing technological development and competence within the fields of water, environment and health.

DHI's knowledge of water environments represents more than 60 years of dedicated research, technology development, and real-life experience from more than 140 countries, including all Nordic European countries. DHI strive to make this knowledge globally accessible to clients and partners by channelling it through their local teams, tailored solutions, and industry-leading software products.

DHI has developed standards and tools to optimise wind farm designs and ensure their safe and sustainable construction, operation, and maintenance. DHI offers the entire range of noise impact assessments, from source modelling (e.g., offshore wind farm pile driving) to propagation modelling (using an in-house noise modelling software, the underwater acoustic simulator (UAS)) to biological impact assessment using internationally accepted noise criteria. In this project, DHI brought in underwater noise expertise in assessing the impacts of the proposed offshore activities and assessed that these do not negatively affect fish being farmed nor the marine ecosystem.

ÅKP – Blue Maritime Cluster

GCE Blue Maritime was in 2014 granted the status of a Global Centre of Expertise. A major reason for this was the cluster's unique global market position and its important contribution to Norwegian value creation. Global Centre of Expertise are the top level in the Norwegian cluster program and has a national status awarded by the government to the most global and rapidly growing business clusters in Norway. GCE Blue Maritime assist in increased value creation and strengthened attractiveness and position within global value chains, through strategic collaborative projects between the cluster's partners and with external partners.

The GCE Blue Maritime Cluster project is run by the innovation company ÅKP AS and can therefore draw on the extensive expertise and excellent network in this knowledge environment. This includes the NCE Legasea and the Norwegian Catapult Digicat. GCE Blue Maritime is managed by a distinguished and balanced steering committee, consisting of key people from the maritime business in the region, county and NTNU Ålesund.

Today, the GCE Blue Maritime comprises close to 200 members, and one of the important pillars is knowledge building and sharing. In 2023, GCE hosted more than 70 events and workshops with more than 2800 participants, originating from more than 350 different companies and public bodies. The content of these events ranged from very specific challenges related to IACS (the upcoming maritime Cyber Security Standard), to more generic and politically oriented topics. In addition, GCE Blue Maritime has close to 3.700 followers on LinkedIn and almost 170.000 visitors on our homepage.

In the project, the role of GCE will primarily be related to the dissemination activities, but GCE will also contribute to the overall project management.

Fyrbodals kommunförbund (Fyrbodal Association of Local Authorities)

Fyrbodal Association of Local Authorities (Fyrbodal) is one of four regional municipal associations in Västra Götaland. Through the association, 14 member municipalities work together for sustainable development. Fyrbodal aims to strengthen the region's competitiveness, promote sustainable development, and improve the quality of life for our approximately 260,000 inhabitants.

Fyrbodal has a strong interest in the coexistence of offshore wind power and aquaculture, as it aligns with the region's strategic goals for sustainable development, economic growth, and the green transition. The region has favourable natural conditions for both renewable offshore energy production and a growing blue economy, making it particularly relevant to explore how these activities can operate in harmony within shared marine spaces.

By exploring coexistence, Fyrbodal aims to harness synergies between two future-oriented sectors—energy and aquaculture—which can contribute to increased regional self-sufficiency, job creation, and technological innovation. At the same time, there is a strong commitment to safeguarding ecosystem services and ensuring that the expansion of offshore wind power occurs in a way that respects environmental concerns and the interests of local communities.

The association also sees joint planning of these activities as a way to streamline marine spatial planning and reduce potential conflicts between different users of the sea. By participating in OFFWOFF Fyrbodal will learn more about how we can contribute to a more sustainable and integrated coastal and marine management.

Nordic Innovation & "A Sustainable Ocean Economy"

Nordic Innovation is an organisation under the Nordic Council of Ministers with the aim to make the Nordics a pioneering region for sustainable growth by promoting entrepreneurship, innovation and competitiveness in Nordic businesses. Nordic Innovation supports the Nordic prime ministers' vision that the Nordic region will become the most sustainable and integrated region in the world in 2030. In 2020, the Nordic ministers for business and innovation launched eight initiatives for a greener post-COVID-19 business sector 2021-2024, and Nordic Innovation work to fulfil the goals of the Nordic Vision 2030. The eight initiatives will make it easier for Nordic businesses to operate across borders and support the vision for the Nordic region to be the most sustainable and integrated region in the world by 2030.

Together, the eight initiatives support sustainable solutions, circular economy, digitalisation and innovation:

- The Nordic region as leading within green transport.
- The Nordic region as leading within a competitive and sustainable building and construction sector with reduced climate and environmental impact.
- The Nordic region as leading within circular and sustainable business models.
- The Nordic region as leading within sustainable mineral production.
- The Nordic region as leading within smart connectivity.

- The Nordic region as leading within digitalisation, AI and responsible application of data.
- The Nordic region as leading within health technology and life science.
- The Nordic region as leading within the development of a sustainable ocean economy.

It is within the initiative "A Sustainable Ocean Economy" that the OFFWOFF project applied for and received funding. The Sustainable Ocean Economy programme aims to put the Nordic region as a frontrunner in the development of a sustainable ocean economy. The ocean, seas, coastal and inland waters form a single system on which all life depends on and since they are also places of leisure, well-being and trade, they represent an ever-growing area of importance for the economy and future growth of the Nordic region.

For most sectors dependent on the ocean, 'business as usual' will not be enough. The Nordic countries have a unique opportunity to take a leading role at the international level to transform the ocean economy in a sustainable way.

Methods

The OFFWOFF project has been structured into five work packages (WPs) to address the specific challenges and opportunities of co-locating floating offshore wind farms with offshore fish farming. This structure has ensured that the project objectives have been comprehensively studied and reported on.

- WP1 investigated the technical, operational and biological feasibility of co-location.
- WP2 analysed the mooring system layout and configuration to address any conflicts between the infrastructure of the wind turbines and aquaculture.
- WP3 assessed the environmental impacts of noise levels from the project, focusing on underwater noise from construction and operation and how that may affect the farmed fish and surroundings.
- WP4 has used the findings from the other work packages to make an updated co-location concept and business plan.
- WP5 manages project coordination, stakeholder communication and dissemination.

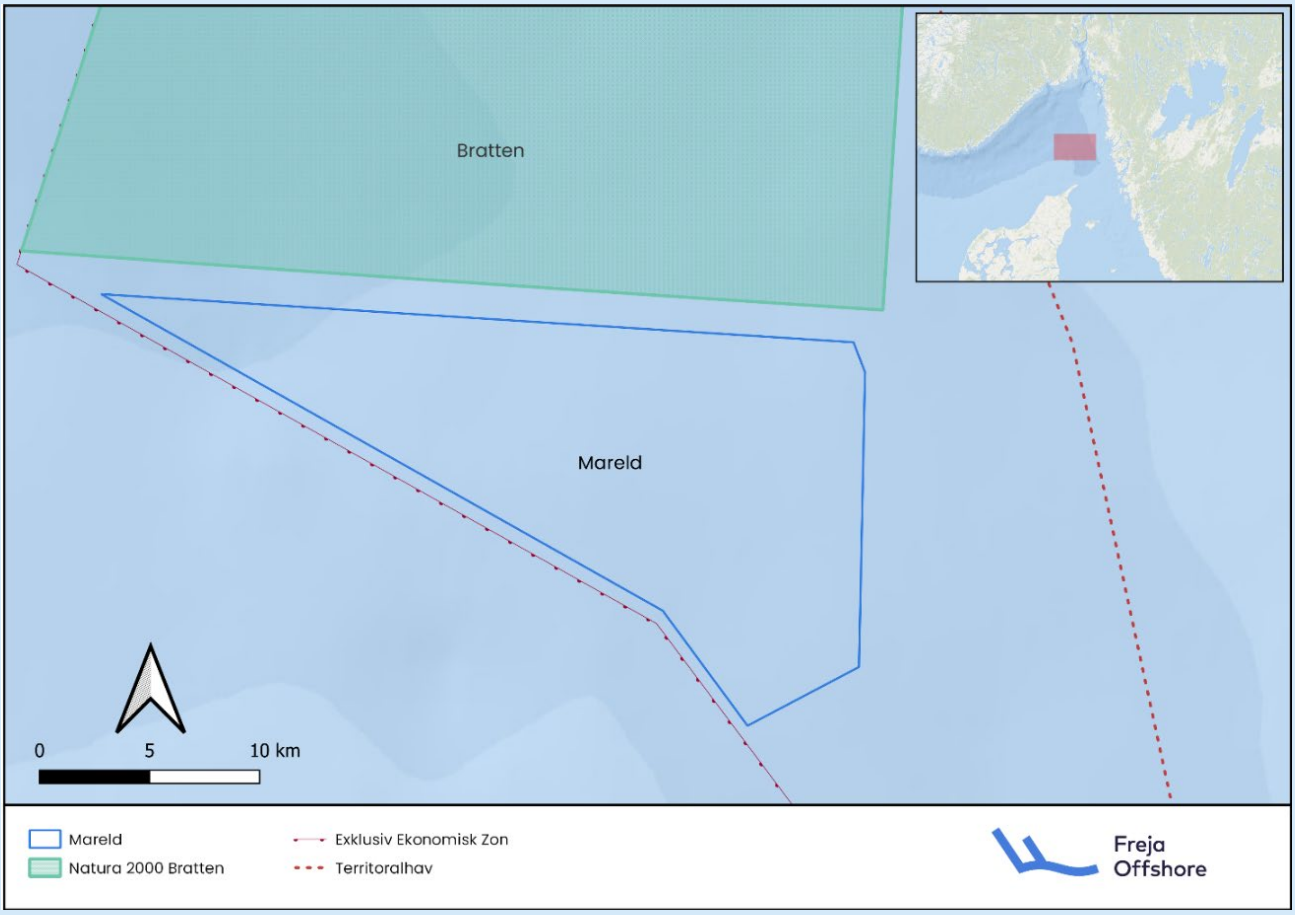
Each WP had clearly defined objectives and expected deliverables. These deliverables are detailed technical reports that directly contribute to the results presented in this report. They are included as attachments to support this report:

- Attachment **A: Metocean Specification Report**
- Attachment **B: Hydrodynamic Analyses Report**
- Attachment **C: Underwater Noise Modelling and Impact Assessment Report**
- Attachment **D: Feasibility of Wind Farm and Fish Farm Coexistence**

Project Case: Mareld Offshore Wind Farm

The specific case for this project has been the Mareld Offshore Wind Farm, currently under development by Freja Offshore. The Mareld wind farm area is planned in the Swedish Economic Zone (SEZ) in Skagerrak, approximately 35 km west of the mainland of the Swedish coast. The Mareld area is judged to have favourable wind conditions. Its location far out at sea will allow Mareld to produce large and reliable amounts of renewable energy. Once completed, the wind farm will deliver renewable electricity equivalent to two-thirds of Västra Götaland's current electricity consumption — a significant contribution to the region's green transition.

Figure 33-1 Mareld Offshore Wind Farm location. Credit: Freja Offshore.



The water depth at the Mareld field will require the use of floating wind turbines. These are the main components of a floating offshore wind farm, together with the foundations and associated mooring lines and anchors, offshore substations and inter-array cables between the turbines and substations.

Offshore wind technology, particularly floating offshore wind, is advancing rapidly, while permit processes can be lengthy. As a result, it is not feasible to propose a final design or a specific technology alternative for the offshore wind farm due to uncertainties related to for instance: installation techniques, foundation types, and turbine size. To address this, the industry has adopted the practice of defining a project design envelope (PDE) that is built up from maximum parameters obtained from modelling various scenarios and technologies. This principle enables the developer to choose the most suitable project specifications from within the design envelope, thereby defining a scenario that stays within its constraints and determining the optimal option for implementation.

Of floating foundations and mooring systems, Freja currently has all major technology concepts under consideration. These include semi-submersible platforms, spar-boys, barge and tension leg platforms, as shown in **Figure 3-2** . The final technology selection for Mareld has not yet been made and will depend on further site-specific, technical and environmental assessments.

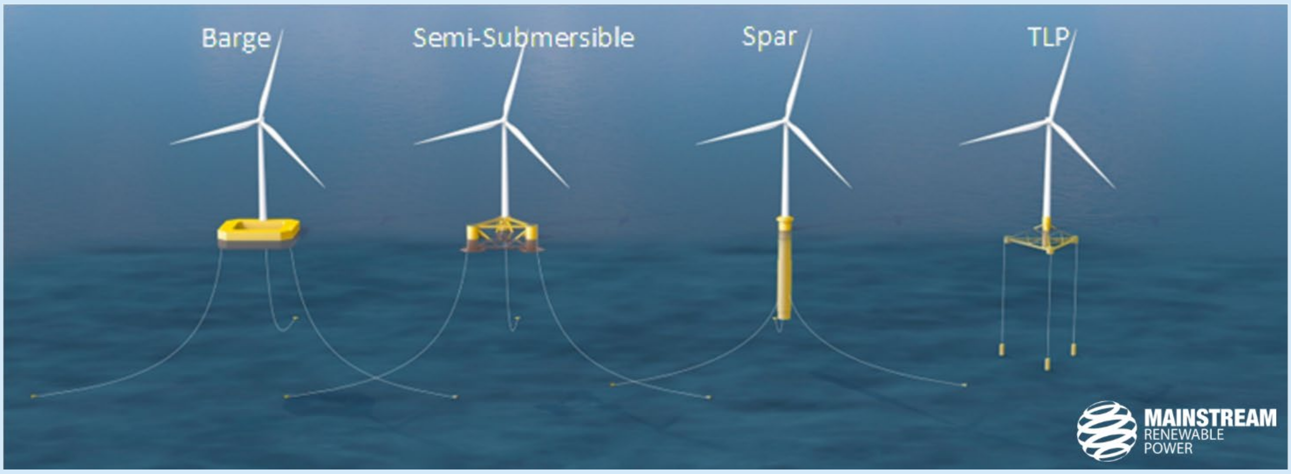


Figure 3-2 Categories of Floater foundations. Credit: Mainstream Renewable Power (image inspired by standard red. DNV-ST-0119).

Understanding the constraints and potential flexibility of the different technologies is essential for identifying co-location opportunities and ensuring compatible configurations. From a technical perspective, co-location must be planned to avoid interference and ensure operational safety. This includes:

- **Defining technical interfaces** between wind power infrastructure and aquaculture installations (e.g., anchoring systems, maintenance zones).
- **Coordinating marine operations**, such as vessel traffic and scheduling, to ensure efficient and safe access for both sectors.
- **Designing data-sharing platforms** for real-time monitoring and environmental reporting across both operations.

By addressing these aspects early, Freja Offshore can ensure that co-location becomes a feasible, low-risk, and potentially cost-effective addition to the overall project plan.

Technical Feasibility of Co-Locating SubFarm Units within the Mareld Wind Farm

The analysis assesses the technical feasibility of integrating SubFarm aquaculture systems within the layout of the Mareld floating offshore wind farm. The evaluation is based on spatial, environmental, and operational compatibility, using the following methodological considerations:

Early planning

By including assessments of other activities in the early planning phase of a project, it can be more easily included during construction. Assessments were therefore also made to list steps and considerations necessary to plan for at the early stage of planning an offshore wind project.

Environmental Parameters: Water Depth, Wave Height, and Sea Currents

Site suitability was first assessed based on key **metocean criteria** essential for submerged aquaculture:

- **Water depth** exceeds 100 m across the site, meeting the requirement for vertical cage positioning and secure mooring.
- **Wave height** (Hs < 10 m) is within the tolerance of SubFarm's feed platform design and mooring stability.
- **Sea currents** were analysed to ensure adequate flow for water exchange while avoiding excessive force on structures. The SubFarm system is designed for average current speeds below 1 m/s.

These parameters were verified using bathymetric data, historical oceanographic datasets, and engineering design thresholds.

Mooring Line Footprints: Wind Turbines and Fish Farms

A central part of the feasibility study involved mapping the **horizontal footprint** of mooring systems:

- **Wind turbine moorings** typically extend 600–1,000 m horizontally, depending on water depth and mooring type (taut vs. catenary).
- **SubFarm moorings** span 400–600 m and are engineered to remain outside turbine safety zones.

Detailed spatial analysis ensured that SubFarm units could be placed within turbine arrays without **overlapping mooring lines** or compromising the station-keeping of either system.

In-Field Cables

The layout review accounted for **inter-array cables and export cables** connecting the wind turbines. SubFarm placements were planned to:

- Avoid cable corridors
- Maintain adequate clearance from electrical infrastructure
- Ensure future access for inspection and repair activities

These considerations were informed by standard wind farm cable routing practices and risk minimisation protocols.

Operational Restrictions and Safety Zones

Vessel operations associated with SubFarm (e.g., smolt transfer, feed delivery, harvesting) were analysed in light of offshore wind **safety exclusion zones**, typically set at **500 m radius per turbine**.

The analysis confirmed that:

- All SubFarm-related vessel activities can be conducted **outside turbine safety zones**

- **Critical manoeuvres** (e.g. cage towing, well boat operations) are feasible under controlled weather conditions
- Shared use of **Crew Transfer Vessels (CTVs)** and common land-based logistics is possible without compromising turbine access or safety protocols

Operational planning is aligned with best practices from the offshore wind and aquaculture industries.

Assessment of Biological Feasibility for Offshore Salmon Farming

The analysis in Chapter 4 evaluates the **biological suitability** of the Mareld offshore site for Atlantic salmon farming. The assessment is based on established environmental tolerance ranges for salmon and site-specific data on key water quality parameters. The methodology includes the following elements:

Acceptance Criteria for Environmental Conditions

The evaluation is based on widely accepted biological thresholds for Atlantic salmon. These define the environmental envelope required for survival, health, and growth:

Parameter	Optimal Range	Acceptable Range	Critical Limits
Temperature	8–16 °C	3–20 °C	Mortality risk > 23 °C
Salinity	30–35 ppt	25–37 ppt	Below 15 ppt or prolonged extremes
Oxygen	>100% saturation	>80% saturation	Welfare risk < 70%
Sea current	0.1–0.5 m/s (stable)	>0.05 m/s, <0.8 m/s (≤4 h)	Stagnant or extreme flow conditions

These ranges are based on research from institutions such as Nofima, the Institute of Marine Research (Norway), and international aquaculture literature.

Site Data Collection and Evaluation

Data for Mareld was sourced from the **Copernicus Marine Environment Monitoring Service** and includes monthly averaged values for:

- **Water temperature** at surface and 50 m depth
- **Salinity** at surface and 50 m
- **Current speeds** at surface and depth
- **Oxygen saturation** (surface only due to data limitations)

Each parameter was compared to the salmon acceptance ranges to assess biological feasibility.

Assessment Approach

- **Temperature and salinity** were found to fall within optimal or acceptable ranges year-round, supporting robust salmon growth and health.
- **Oxygen levels** at the surface exceeded 100% saturation on average, indicating high water quality, though **depth measurements are needed** to confirm subsurface suitability.
- **Sea current** speeds were generally adequate, but minimum values near zero suggest the possibility of stagnation. Due to the lack of temporal resolution, further **in situ measurements** are recommended to confirm that current speeds remain above critical thresholds for sufficient water exchange.

Hydrodynamic Analysis of Co-Location between SubFarm and Floating Wind Turbines at Mareld

This method statement outlines the procedures, assumptions, and tools applied to assess the hydrodynamic feasibility of co-locating a Subfarm aquaculture system within a floating offshore wind farm at the Mareld site in the Skagerrak, as part of the OFFWOFF project.

Objective

The analysis was undertaken to:

- Provide hydrodynamic input data for noise propagation modelling conducted by DHI.
- Evaluate the motion response, spatial compatibility, and mooring interactions between Subfarm and two floating wind turbine types under extreme metocean conditions.

Systems Modelled

Three offshore structures were included in the simulation models:

- **Subfarm Fish Farm System**: Comprising a central feed barge and 12 submerged cages, modelled with simplified hydrodynamic equivalents.
- **Spar Buoy Wind Turbine**: 5 MW rated, 130 m structural length, moored with 3-leg wire and chain system.
- **Semi-submersible Wind Turbine**: 15 MW rated, semi-sub structure with 3-leg chain mooring system.

Modelling Environment

- **Simulation Tool**: OrcaFlex (industry-standard non-linear time domain simulation software)
- **Modelling Parameters**:
    - Location: Mareld offshore wind lease site (40 km west of Lysekil, Sweden)
    - Water Depth: 200 meters

- Metocean Conditions:
  - 100-year omni-directional sea state
  - Significant wave height (Hs): 7.3 m
  - Peak period (Tp): 13.3 s
  - Uniform current: 0.62 m/s
  - Wind speed at 143 m elevation: 9.7 m/s

Simulation Procedure

- Each system was modelled with full hydrodynamic fidelity, including platform geometry, mooring configurations, and degrees of freedom.
- **Simulation Duration**: 1-hour time-domain simulations (3600 seconds).
- **Wave Headings**: Simulations were performed at 0°, 45°, and 180° to capture directional effects.
- **Analysis Scenarios**:
  - Standalone wind turbine simulations (Spar and Semi-sub) for power and motion assessment.
  - Co-located Subfarm and Semi-sub system to assess spatial and dynamic compatibility.
  - Feed barge mooring pre-tension tests with rope and heavy chain scenarios.

Output Data and Post-Processing

The following outputs were extracted for interpretation and for delivery to DHI:

- Translational offsets and motion envelopes for all systems.
- Mooring line tensions and structural accelerations.
- Power output time series for wind turbines.
- Hydrodynamic load statistics on Subfarm feed barge and cages.

Assumptions and Simplifications

- Subfarm cages were represented by a 6 DOF buoy to reduce computational demand while preserving key hydrodynamic characteristics.
- Co-location analysis was primarily qualitative, with limited numerical overlap analysis.
- Mooring systems assumed idealised load-sharing and seabed conditions.

Verification and Quality Assurance

- All modelling inputs, boundary conditions, and assumptions were reviewed and verified by experienced engineers.
- Results were cross-validated through comparative static and dynamic visualisation of system behaviours.

Noise Impact Assessment

DHI uses a three-step approach to estimate how far and wide underwater noise from human activities might affect marine animals:

1. **Defining the Noise Source:**
   The process begins by identifying the loudness of the sound and its frequency range. This characterisation relies on actual measurements, which are adapted to suit the specific conditions of the project.
2. **Numerical propagation modelling (Modelling how the sound travels underwater):**
   Sound propagation is simulated using a computer model known as the *Underwater Acoustic Simulator*, developed by DHI. This model is based on established scientific methodologies and calculates how sound propagates (travels) in various directions and frequencies. The propagation is highly dependent on the water conditions (temperature, salinity, pH-value and the water depth profile).
3. **Calculation of biological effects (Estimating how the noise affects marine life):**
   Internationally recognised thresholds are applied to assess potential impacts on marine species such as mammals and fish. These effects include behavioural changes, temporary hearing threshold shifts, and recoverable or auditory injuries. If thresholds have not yet been defined, the latest literature is reviewed.

To enhance accuracy, the site's sound levels were analysed in different directions and spatial maps indicating the areas where the sound would be audible, and the assessed impacts are expected were produced.

The following acoustic scenarios were assessed within WP3:

1. **Underwater noise from wind farm installation** – Evaluating noise generated by different anchoring methods, including pile driving and suction anchor installation, with and without mitigation measures.

2. **Underwater noise from aquaculture installation** – Assessing the noise impact of suction anchors used for fish farm mooring.

3. **Operational and maintenance noise** – Modelling continuous noise from wind turbines, and fish farm operations, as well as discussing possible effects of noise caused by mooring lines and service vessels.

Economic and Value Creation Analysis

The economic analysis assesses the financial viability and regional impact of offshore fish farming at the Mareld site. The methodology is based on the following five elements:

Pre-Tax Cash Flow Analysis

Financial projections are based on a pre-tax discounted cash flow (DCF) model. This includes estimated capital investment (CAPEX), annual operating costs (OPEX), and revenues from salmon production. Key indicators, NPV, IRR, annual net cash flow, and payback period, are used to assess investment performance.

Phased Development

The investment is phased to reflect a realistic build-out timeline:

- A pilot unit (3,000 tons/year) enables early testing.
- Four full-scale SubFarm units (12,000 tons/year each) are added in sequence.

This allows for gradual capital deployment and operational learning.

Capital Cost Estimates

CAPEX is based on:

- SubFarm's engineering and design data
- Supplier quotes for equipment and installation
- Industry benchmarks for offshore aquaculture infrastructure

Unit costs are expressed per kg of annual capacity.

Operating Costs and Revenue Assumptions

OPEX is based on 2023 data from the Norwegian Directorate of Fisheries, reflecting smolt, feed, labour, and other typical inputs. Salmon prices use recent Norwegian export prices as a proxy for the Swedish market.

Value Creation Benchmarking

Regional value creation is estimated through analogy with Rogaland, Norway, a biologically and operationally comparable aquaculture region, with production volumes representative of the realistic potential for the Swedish west coast. Public data on production volumes, employment, and value creation are used to project the potential economic impact on the Swedish west coast under similar conditions.

Strategic participation

Our strategic approach to participating in seminars, conferences, workshops, and webinars as part of the dissemination of the project has been continuously managed, guided by relevance, availability, and incoming invitations. Leveraging the team's expertise across different fields, we have actively presented our work on coexistence within the OFFWOFF project. We have consistently responded positively to invitations and opportunities from various stakeholders, using them as platforms to promote the project, strengthen collaboration, and share knowledge and insights.

Although the activities have predominantly taken place in Sweden and Denmark, we aim to expand our engagement in Norwegian arenas in Q2 and Q3 2025 to enhance the project's visibility and strengthen cross-sector collaboration.

Results

Fish Farming Concept: SubFarm Co-Location at Mareld

SubFarm Design and Function

The SubFarm system represents a novel approach to offshore aquaculture, built around a low-profile, circular feed platform surrounded by up to twelve submerged fish cages. Each cage holds up to 200,000 fish, with a volume of 40,000 m³, enabling a system-level annual production capacity of 12,000 tons.

The submerged design improves resilience to rough weather, enhances fish welfare, and reduces interaction with predators. Each cage is tethered by a single-point mooring and positioned vertically via winch, allowing flexible placement within the water column to optimise biological conditions.

Feed, power, and control are delivered via umbilicals connecting each cage to the central feed platform, which also serves as a redundancy mooring in case of single-point failure.

Figure 4-1 SubFarm Fish Cage Structure and **Figure 4-2** show the cage structure and a 12,000 ton Subfarm fish farming system.

Figure 4-1 SubFarm Fish Cage Structure

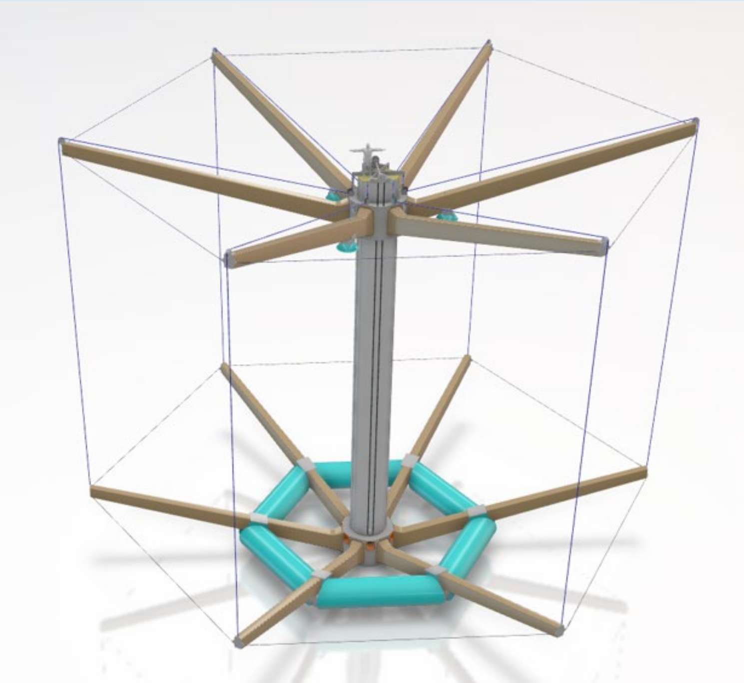
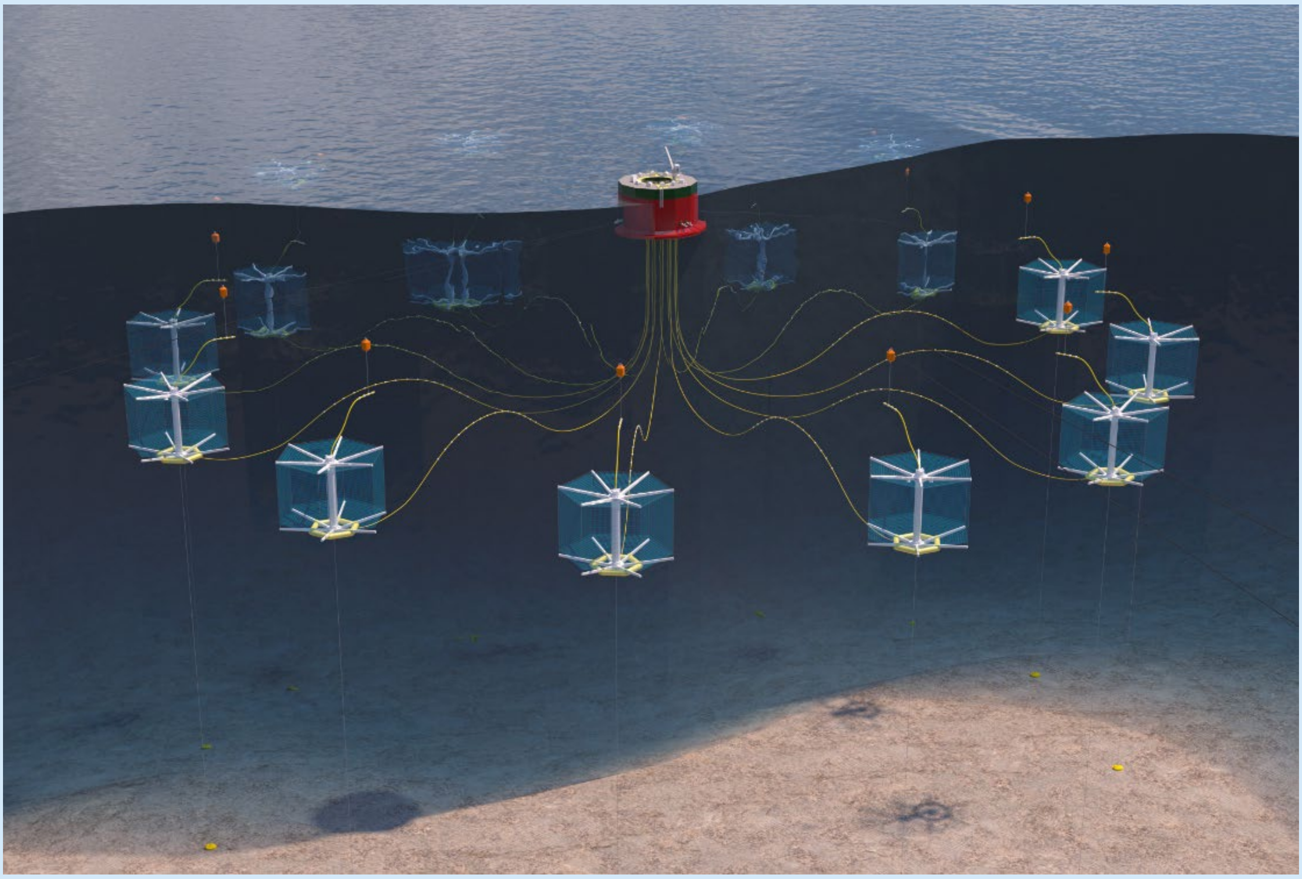


Figure 4-2 SubFarm 12,000 tons Aquaculture System



Integration with the Mareld Wind Farm

The Mareld site offers suitable conditions for submerged aquaculture, with depths over 100 m and moderate currents. The proposal includes installing four SubFarm units within the wind farm, yielding a combined production of 48,000 tons/year. With Sweden's annual fresh salmon consumption around 5,000 tons, this development could significantly improve national food security.

Placement of the fish farms will:

- Ensure a minimum of 4 km spacing to reduce disease transfer
- Avoid conflict with turbine moorings and cables
- Be located in areas with favourable wave and current conditions
- Minimise operational overlaps with wind infrastructure

Mooring and Spatial Compatibility

The feasibility of co-locating SubFarm units within Mareld hinges on spatial planning. SubFarm's mooring footprint (400–600 m radius) fits between turbine safety zones, which typically have 500 m buffers. Layout planning must consider:

- Wind turbine spacing (typically 1.5–2 km for 15 MW turbines)
- Mooring dynamics and seabed conditions
- Avoidance of infrastructure interference

Collaborative layout simulations and stakeholder coordination will be needed to optimise shared ocean space usage.

To satisfy the accidental case of two mooring line failures, the wind turbines around the SubFarm need to have at least three mooring lines in the group facing away from the Subfarm.

Operational Requirements and Logistics

SubFarm operations include smolt delivery, feeding, maintenance, inspection, harvesting, and emergency procedures. These are performed using:

- Well boats (smolt transfer, harvesting)
- Workboats (sampling, inspections, cage towing)
- Pellet carriers (feed delivery)
- Crew Transport Vessels (personnel transfer)

Operations are weather-dependent and planned to avoid proximity to wind turbine safety zones.

Synergies with Wind Farm Operations

Operational synergies between SubFarm and Mareld include:

- Joint use of installation vessels and planning
- Shared crew transfer services (CTVs)
- Potential overlap in ROV inspections
- Common land base for logistics, storage, and personnel facilities

These shared resources can reduce costs and improve the sustainability profile of the co-located operations.

Water Quality Assessment

Water quality is a critical factor for the biological feasibility of offshore salmon farming. At Mareld, four key environmental parameters were assessed to evaluate the site's suitability for Atlantic salmon: temperature, salinity, current speed, and oxygen saturation. These were evaluated using data from the Copernicus Marine Environment Monitoring Service.

Temperature

Atlantic salmon thrive in water temperatures between 8 °C and 16 °C, with acceptable survival down to 3 °C and up to 20 °C. Mareld shows:

- **Surface temperatures**: Mean 10.4 °C, with a range of 4.6–17.7 °C
- **50 m depth**: Mean 9.0 °C, range of 5.6–15.2 °C

These conditions fall well within optimal and acceptable thresholds for both welfare and growth, indicating a biologically supportive thermal profile.

Salinity

Atlantic salmon are euryhaline but generally perform best in stable marine salinities. At Mareld:

- **Surface salinity**: Mean 29.5 ppt (min 13.7 ppt, max 34.6 ppt)
- **50 m depth**: Mean 34.3 ppt (min 32.5 ppt, max 35.7 ppt)

These values are consistent with natural North Atlantic conditions, and the deeper water salinity is stable and well-suited for salmon.

Currents

Water currents play a key role in oxygen replenishment and waste removal. Research suggests currents should exceed 0.05 m/s consistently and not exceed 0.8 m/s for extended periods.

- **Surface current**: Mean 0.2 m/s (min 0.01 m/s, max 0.7 m/s)
- **50 m depth**: Mean 0.15 m/s (min 0.002 m/s, max 0.48 m/s)

Although average values are within an acceptable range, low minimum speeds raise concern about possible stagnant periods. Since the available data lacks temporal resolution (i.e. duration), further site-specific measurements are necessary to assess whether low-flow episodes last long enough to impact fish health.

Oxygen Saturation

Oxygen levels above 80% are necessary for maintaining welfare, and levels above 100% are recommended for optimal growth.

- **Surface oxygen saturation**: Mean 104%, with a range of 82–141%
- **No available data** for deeper layers, which are critical for submerged cages.

While surface conditions appear favourable, the absence of deepwater oxygen data introduces uncertainty. Oxygen saturation at cage depth must be monitored over time to ensure levels remain sufficient during warm periods or periods of low current.

Results of the Underwater Noise Assessment

DHI was responsible for executing the following four sub-work packages related to underwater noise. Their definition is provided below, along with a short description of how DHI approached and implemented them.

1. **Underwater noise from the wind farm installation**
   This work package included the assessment of underwater noise generated by activities associated with the construction of the offshore wind farm. As part of this assessment, models were developed to estimate the noise levels at the source and their propagation in the surrounding marine environment. In

addition, common mitigation strategies were considered and evaluated.

DHI approach and implementation:
There are many different options for the installation of anchors for the floating wind turbines. The acoustical worst-case is impulsive pile driving. Therefore, a realistic pile driving scenario was defined, and the impacts were evaluated for an unmitigated and a mitigated scenario.

Furthermore, the underwater noise from a suction anchor installation was considered for the installation of the aquaculture, which could be an alternative anchoring technology for the floating turbines.

2. **Underwater noise from the aquaculture installation**
   This work package included the assessment of underwater noise generated by activities linked to the installation of the offshore fish farm. Noise levels were estimated using source and noise propagation models.

   DHI approach and implementation:
   The preferred installation technique for the fixation of the aquaculture farm is a suction anchor. Therefore, a modelling approach for the evaluation of the pumping and vessel noise caused by the suction anchor installation was developed, and the impacts that could result from these aquaculture installation activities were investigated.

3. **Underwater noise from the operations and maintenance**
   This work package included the estimation of underwater noise levels generated during operations and maintenance of the combined offshore farms.

   DHI approach and implementation:
   The operational and maintenance noise of the combined farms was assessed as follows. The operational noise of all floating turbines and fish farms was modelled numerically. The underwater noise caused by the operation of the aquaculture was combined with the underwater noise emitted by the operating turbines, and their cumulative impact is assessed. Furthermore, the effects of the underwater noise caused by mooring lines and supply vessels were discussed.

4. **Assessment of environmental impacts of noise levels**
   This work package included the combination and assessment of noise levels estimated during previous tasks, with a focus on their potential impacts on marine species in the surrounding areas, as well as on the fish species being farmed. The outcome provides a comprehensive environmental assessment of the cumulative underwater noise impact resulting from the co-location of offshore wind and fish farms.

   DHI approach and implementation:
   The impacts on harbour porpoises, seals, and fish caused by the underwater noise emitted in the different scenarios were evaluated by combining internationally accepted criteria and state-of-the-art research results with the modelled

underwater noise levels. Furthermore, a literature study was conducted to identify thresholds for the farmed fish species.

The results of the underwater noise modelling, literature reviews of thresholds applicable to the farmed salmon, and trout and on the possible influence of service vessel noise can be summarised as follows:

Underwater noise from wind farm installation: For the installation of the anchors for the wind turbines, a pile driving noise scenario was considered, with and without noise mitigation measures. The unmitigated scenario is only provided for reasons of completeness, since the Natura 2000 permit only allows mitigated pile driving.

Two outcomes of the pile driving activity are presented below to illustrate some key findings. These are the maps for the behavioural impact of harbour porpoises and the hearing impairment for the farmed fish species salmon and trout.

Within Figure 4-3 the very high frequency weighted sound pressure level is displayed together with the two adjacent Natura 2000 areas and the impact area showing the expected impact ranges for a behavioural reaction of the harbour porpoise. The very high frequency weighting is conducted to account for the hearing sensitivity of the harbour porpoise.

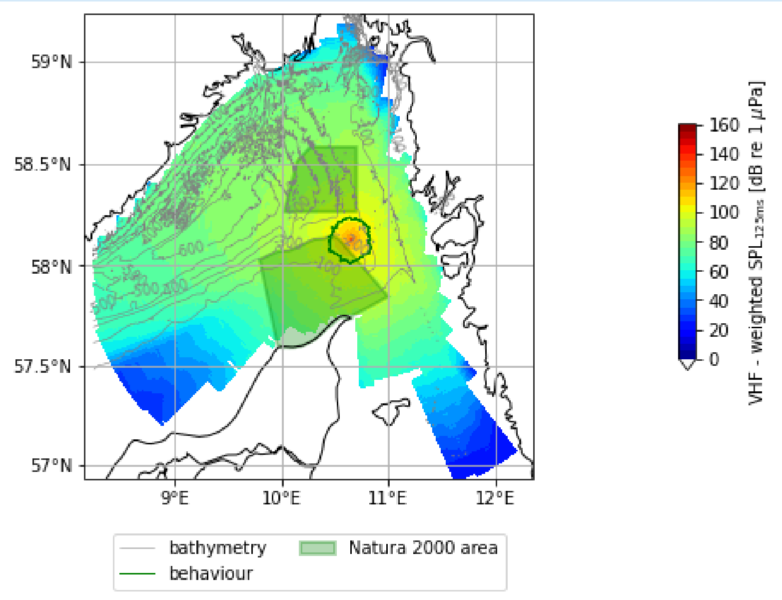
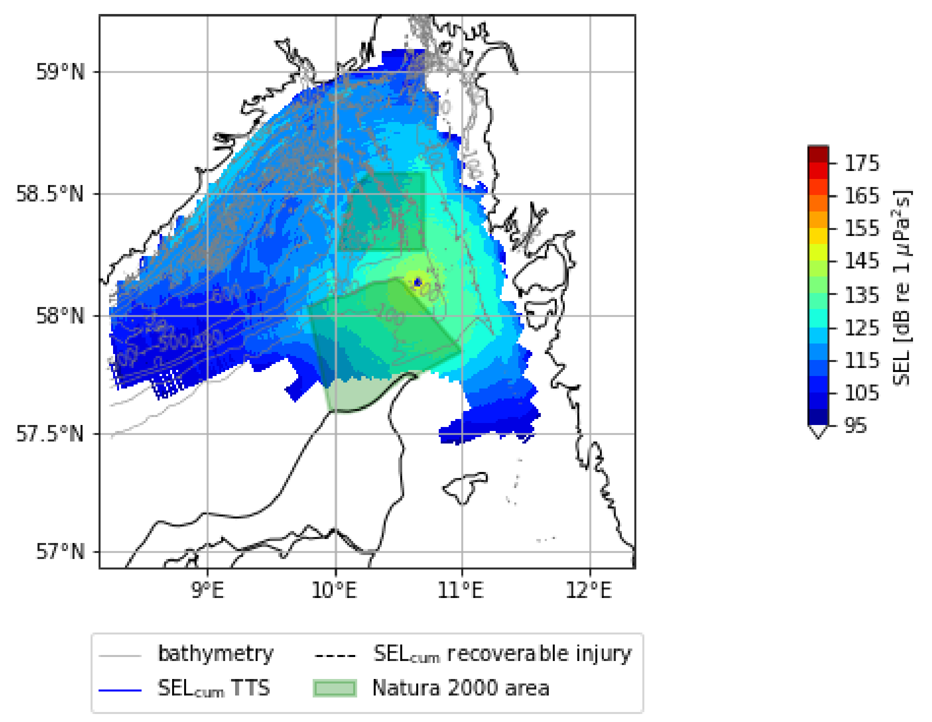


Figure 4-3. Map of the very high frequency weighted sound levels caused by mitigated pile driving and the impact area for a behavioural response of the harbour porpoise.

An important aspect of the OFFWOFF project is the evaluation of the noise effects on the farmed fish species. Therefore, the sound levels were only evaluated at the dedicated depths of the fish cages. These are planned to be located 20 m to 80 m below the sea surface. Within Figure 4-4 the maximum sound exposure levels evaluated in the fish cages' depths and the expected temporary threshold shift (TTS) and recoverable injury impact areas are displayed therein too. For the farmed salmon and trout, a behavioural threshold for pile driving noise could not be identified during the conducted literature review for the farmed fish.

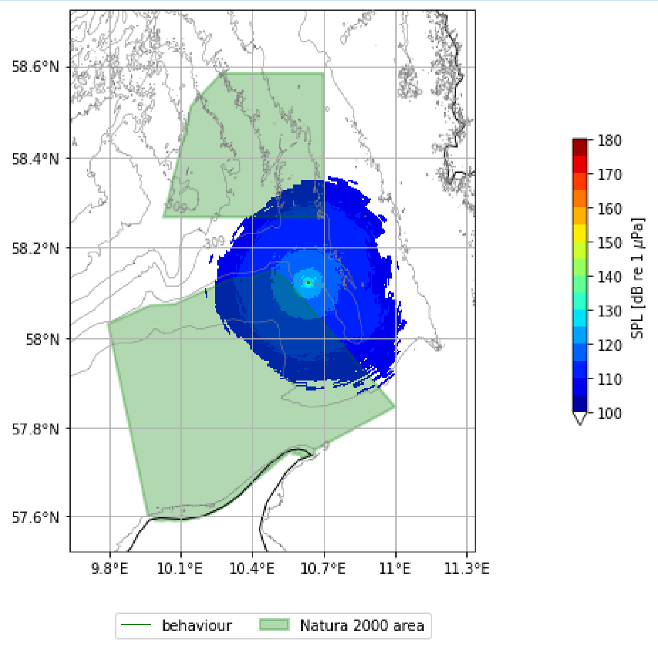
Figure 4-4. Map of Sound Exposure Level resulting from mitigated pile driving and the impact areas for auditory injuries of the farmed fish.



The outcome of the pile driving noise modelling can generally be summarised as follows: The highest impact ranges were observed for unmitigated pile driving. The consideration of noise mitigation measures significantly reduces the impact ranges of all considered effects for the harbour porpoise, seals, and fish with a swim bladder involved in hearing. However, overlapping impact areas with at least one of the Natura 2000 areas may also occur for mitigated pile driving, especially for the behavioural response of harbour porpoise and TTS of seals.

Underwater noise from aquaculture installation: For the fixation of the aquaculture, the underwater noise caused by the installation of a suction anchor was assessed. Such an anchoring technique could also be used for the fixation of the floating wind turbines. The assessed impacts of all considered species led to impact ranges of less than 100 m. The acoustic footprint of the suction anchor installation is displayed within Figure 4-5. Therein, the sound pressure levels that are above the ambient noise and the behavioural impact area for harbour porpoises are displayed. Since the impact area is very small and centred around the source location, it is not well visible.

Figure 4-5. Map of the unweighted sound pressure level at the Mareld OWF resulting from suction anchor installation work with the behavioural impact area for harbour porpoises. Only sound levels above the ambient noise are shown.



Wind farm and fish farm operational noise: The assessment of the operational noise from the wind farms and fish farms showed that only small local impact areas centred around each turbine and fish farm can be expected. The underwater noise added due to the fish farming activity is leading to a minor increase in the underwater acoustic footprint of the combined farms compared to the scenario with only wind turbines. Within Figure 4-6 the sound pressure level caused by the operation of the wind turbines and the fish farms is displayed.

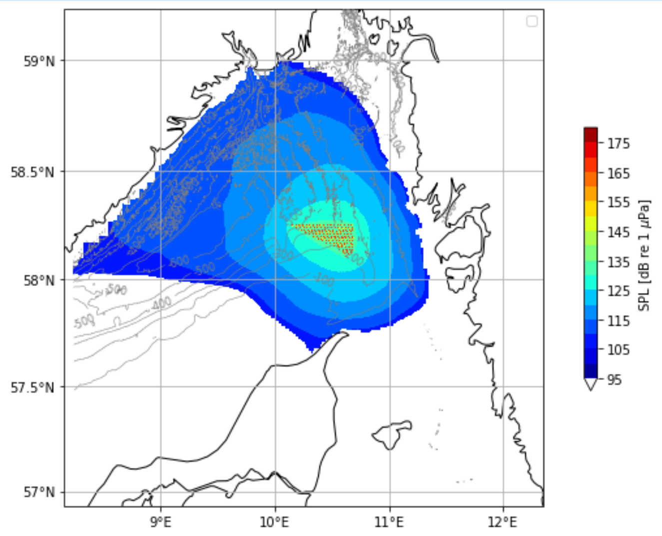


Figure 4-6. Map of the unweighted SPL at the Mareld OWF caused by the operation of the floating wind and the fish farm. Only sound levels above the ambient noise are shown.

Farmed salmon and trout sensitivity to noise: While farmed salmon and trout are less sensitive to underwater noise, stress and behavioural responses may occur at lower thresholds than TTS. However, a dedicated threshold for a stress response and a behavioural response threshold for pile driving noise remains uncertain due to limited scientific data. A review of the available literature revealed several data gaps and research needs (see the detailed underwater noise report in Appendix C). These include the absence of species-specific criteria, limited integration of fish mobility into existing models, methodological shortcomings in some studies that hinder the derivation of reliable thresholds, and an overall lack of species-specific research needed to establish definitive criteria.

Service vessel noise: A literature review was conducted for the assessment of possible influences of service vessel noise on the local marine fauna (compare Appendix C). However, given the intensity of the service vessel traffic and typically short ranges of influence, the associated noise is not expected to result in substantial effects on the marine fauna.

All in all, the assessment of the underwater noise confirms that noise mitigation strategies, such as a Hydro Sound Damper system, significantly reduce the impact of pile driving on marine life, even in deep water. Furthermore, it is shown that the underwater noise from a suction anchor installation leads to small local underwater noise impacts.

The assessed operational noise from the wind turbines and the fish farms results in very small local impact areas for all considered effects. Therefore, the farmed fish is expected to not be affected by the operational underwater noise. Furthermore, the assessments also showed that no significant impact of the operational underwater noise of the Mareld OWF to the welfare of harbour porpoises, seals, and wild fish is expected.

Stakeholder Assessment for Offshore Wind-Aquaculture Co-Location at Mareld

Overview

The Mareld project proposes a novel co-location of floating offshore wind and submerged salmon farming, approximately 40 km west of Lysekil, Sweden. This multi-use strategy aims to optimise ocean space, generate renewable energy, and build a sustainable aquaculture industry. Success will depend on addressing stakeholder interests, balancing environmental considerations, and enabling regional development.

Strategic Integration from Early Stages

To ensure that co-location becomes a functional and valuable component of Mareld, it should be considered from the early stages of spatial design, permitting, and stakeholder dialogue. This means:

Reserving appropriate space within the project area for potential aquaculture operations, taking into account safety zones, navigational access, and environmental conditions.

Conducting compatibility assessments to identify the types of aquaculture (e.g. shellfish, algae, closed-containment fish farming) best suited to the local marine environment and operational footprint of the wind farm.

Collaborating with potential aquaculture operators early in the planning process to explore technical requirements, business models, and regulatory considerations.

Including co-location in the Environmental Impact Assessment (EIA) and marine spatial planning documentation to demonstrate a multifunctional use of the sea aligned with policy goals.

Co-location presents an opportunity to strengthen trust and build long-term relationships with local stakeholders through early stakeholder engagement and local partnerships. The following steps are identified as key to sustainable project development:

- **Engaging coastal communities and the fisheries sector** in dialogue about shared use of space, potential benefits, and areas of concern.
- **Exploring local partnerships** with aquaculture startups, research institutions, or food producers to anchor the co-location in regional development.
- **Using the co-location initiative as a platform for collaborative monitoring**, involving both sectors in marine biodiversity and ecosystem tracking.

This approach can not only increase local acceptance of the Mareld project but also create new regional value chains and promote innovation.

Key Stakeholder Groups

The key stakeholder groups identified are summarised in **Table 4-1**.

Table 4-1 Key Stakeholder Groups

Stakeholder Group	Level	Role/Interest
Local Fishing Communities	Local	Concerns over access to traditional fishing grounds and potential livelihood impacts.
Coastal Municipalities	Local	Economic development, employment opportunities, and environmental considerations.
Marine Businesses	Local	Opportunities in logistics, maintenance, and supply chain services.
Environmental Organizations	Local/Regional	Monitoring ecological impacts and advocating for sustainable practices.
Regulatory Authorities	Regional	Oversight of compliance with marine spatial planning and environmental regulations.
Research Institutions	Regional	Engagement in innovation, data collection, and advancement of marine technologies.

Potential Impacts

- **Economic**:
  Each SubFarm system could create ~60 jobs (30 offshore, 30 onshore). Co-location enables industrial diversification and infrastructure investment. Local businesses may need support to scale capacity and secure skilled labour.
- **Environmental**:
  Wind farms can act as artificial reefs, enhancing biodiversity, but co-located aquaculture introduces risks of waste discharge, habitat disruption, or disease if not properly managed. Environmental monitoring and mitigation plans are essential.
- **Social**:
  The project can stimulate regional pride and long-term development. Transparent dialogue is critical to ensure local support and equitable benefit distribution.

Co-Location Considerations

- **Noise & vibration** from turbines could affect fish welfare – ongoing assessments are required.
- **Construction activity** may temporarily disturb marine ecosystems.
- **Vessel traffic** introduces minor risks of collision and biosecurity concerns.
- **Electromagnetic fields (EMFs)** from subsea cables require further study regarding effects on fish.

These risks can be managed through best practices in design, siting, and operational planning.

Recommendations

Stakeholder dialogue is key to balancing innovation, ecological stewardship, and community benefit. The Mareld co-location project presents a unique opportunity to set a national example for integrated marine planning. It's recommended to:

- Implement early and inclusive stakeholder engagement processes.
- Develop strong environmental monitoring frameworks.
- Support local workforce training and supply chain development.
- Collaborate with research institutions for long-term system optimisation.

Economic Incentives and Value Creation Potential of Offshore Fish Farming on the Swedish West Coast

Purpose and Scope

This chapter examines the economic case for developing offshore salmon farming within the Mareld floating wind park area. It serves two main purposes:

1. To evaluate the investment potential of deploying SubFarm aquaculture systems within the Mareld wind farm perimeter.
2. To estimate the broader regional economic impacts that a new offshore aquaculture industry could generate on the Swedish west coast, using the Norwegian region of Rogaland as a comparative case.

Investment Case: Offshore Aquaculture at Mareld

The proposed deployment consists of four SubFarm systems, each with a production capacity of 12,000 tons of salmon per year, along with an initial smaller test system producing 3,000 tons annually. In total, this equates to 51,000 tons of annual production capacity.

- **Capital Costs (CAPEX):**
  Estimated at NOK 200/kg for the test phase and NOK 90/kg for the full-scale systems, bringing total investment requirements to approximately NOK 4.7 billion. This includes engineering, system construction, offshore installation, and mooring equipment.
- **Operating Costs (OPEX):**
  Based on cost data from the Norwegian Directorate of Fisheries (2023), operational costs are assumed to be NOK 65/kg. This includes feed, smolt, labour, insurance, and harvesting.
- **Revenue Assumptions:**
  Using a market price of NOK 100/kg for salmon delivered to the Swedish west coast, based on Norwegian export price benchmarks, the project demonstrates strong revenue potential.
- **Financial Projections:**

- **Annual Net Cash Flow (pre-tax):** NOK 1.8 billion
- **Cumulative Net Cash Flow (pre-tax):** NOK 40.9 billion
- **Net Present Value (10% discount):** NOK 4.2 billion
- **Internal Rate of Return (IRR):** 19%
- **Payback Period:** 9 years

These figures indicate a solid and profitable business case, though dependent on achieving technical feasibility, regulatory approvals, and market conditions.

Regional Value Creation: Insights from Rogaland

To assess the broader economic potential for offshore fish farming along the west coast of Sweden, we draw on the case of Rogaland, one of Norway's most established aquaculture regions, which offers a relevant benchmark for marine conditions and industry structure.

- **Rogaland (2023):**
  - **Production:** ~106,400 tons of Atlantic salmon
  - **Value Creation:** NOK 2.3 billion (NOK 1.4 billion direct + NOK 0.9 billion ripple effects)
  - **Employment:** 1,700 jobs (1,000 direct + 700 indirect)
- **Swedish West Coast Potential (estimated):**
  - **Total Value Creation:** SEK 2.4–2.8 billion
  - **Employment Impact:** 1,700–2,000 jobs across farming, logistics, feed production, services, and support industries

Success will depend on strategic investments in smolt hatcheries, port and logistics infrastructure, skilled labour, and supportive policy frameworks.

Disseminations

Effective dissemination is critical for OFFWOFF to transform its technical and socioeconomic findings into real-world impact. By sharing results broadly, through conferences, workshops, webinars and partner channels, the project:

- Informs policy-making and regulatory processes
- Catalyses industry uptake of co-location best practices
- Builds a stronger business case for multi-use marine developments
- Lays the groundwork for new partnerships and scale-up opportunities

Already Held Events

OFFWOFF has actively shared its work across different platforms. In September 2024, the project was presented in Malmö at the *Co-location of Marine Industries* conference, organised by the Swedish Board of Agriculture in collaboration with Nordic Innovation. The conference was part of Sweden's presidency of the Nordic Council of Ministers in 2024, supporting the Nordic Vision 2030—to become the world's most sustainable region by 2030.

Figure 4-7 OFFWOFF presenting at the Co-location of Marine Industries conference in Malmö.

At the annual democratic event Almedalen on Gotland in 2024, Freja Offshore hosted a panel discussion on multi-use marine innovation, highlighting early OFFWOFF insights and stakeholder reactions.

OFFWOFF was pleased that the C2B2 initiative selected the Mareld Park as the focus area for Living Lab West, as it aligned closely with our ongoing work. C2B2 is a Swedish research program that envisions a more sustainable, multi-actor blue economy for Sweden. The program aims to promote participatory governance through processes that move "from data to knowledge to decisions and action." C2B2's three Living Labs, East, West, and North, are innovation experiments conducted in real-life settings across Sweden. These labs bring together actors from multiple sectors and levels of governance, all with an interest in marine environments and marine spatial planning. The OFFWOFF consortium has participated in all of C2B2's Living Lab West activities, two in-person workshops and two digital ones, contributing project findings and insights. To conclude the OFFWOFF project, we were invited to present our findings at a C2B2 Innovation Talk.

OFFWOFF is also represented in *Coexistence for More Seafood*, a project aimed at increasing knowledge on the coexistence of different marine production activities, or "multi-use," at sea, while strengthening the seafood value chain on land. The project focuses on two types of multi-use settings along Sweden's west coast: fixed foundations combined with algae farming in Kattegat, and floating wind power combined with fish farming in Skagerak, i.e the OFFWOFF setup. In December 2024, a webinar was organised in collaboration between the projects "Coexistence for More Seafood" and OFFWOFF.

The OFFWOFF consortium also participated in the *Nordic Workshop on Sustainable Coexistence: Offshore Wind & Blue Food*, organised by Nordregio in Stockholm, May 2025.

Planned & Future Events

In June 2025, the project will be featured in a panel debate on the topic of coexistence at Fosnavågkonferansen 2025. Fosnavågkonferansen is a long-standing annual event held in the coastal town of Fosnavåg, bringing together stakeholders from the maritime and marine industries in the Sunnmøre region and its surrounding cluster of core companies.

The project is also scheduled to be highlighted during the Aquaculture full-day seminar hosted by GCE Blue Maritime Cluster. This event gathers representatives from cluster members in the Northwest region of Norway and offers a platform for dialogue on developments in aquaculture and maritime innovation.

In August, the project will be presented at Aqua Nor—the largest aquaculture exhibition in the world. Held in Trondheim, Aqua Nor serves as a key international arena for the aquaculture industry. Organised by GCE Blue Maritime Cluster, the seminar will focus on co-location and the strategic ambitions of the OFFWOFF project. With more than 25,000 participants from over 80 countries in recent years, Aqua Nor continues to be a vital hub for showcasing technological innovations and fostering international collaboration.

The project will also be presented at Folkemødet on Bornholm in June, by invitation from Nordic Innovation. Folkemødet is Denmark's leading democratic festival, where citizens and decision-makers meet in a unique and open setting to engage in dialogue. The ambition is to strengthen democratic culture through inclusive conversations that foster mutual understanding and bring people closer together.

Partner-Specific Initiatives for Dissemination

Freja Offshore: In addition to disseminating OFFWOFF's results to foster socioeconomic development across the Nordic region, Freja Offshore will integrate the project insights into its external communications as it may bring value in policy and political engagement, enhance stakeholder dialogues and could add value to Freja Offshore's business case and lead to new strategic collaborations.

SubFarm: For SubFarm, further steps involve exploring opportunities for scaling the current business case and engage in new collaborations.

Conclusion

Multi-use of Marine Space: A Strategic Opportunity

Integrating sustainable aquaculture within offshore wind farms is an emerging opportunity for multi-use of marine space – with the potential to support both the energy transition and national food security. Among current offshore wind projects in Sweden, Mareld stands out as one of the most promising candidates for enabling large-scale fish farming in parallel with renewable energy production.

Key Enabling Conditions at Mareld

While other offshore wind farms may also explore co-location opportunities, Mareld offers a rare combination of favourable conditions that make it particularly well-suited for such integration:

- **Sufficient water depth** to support deep-sea aquaculture systems.
- **Turbine spacing** that allows for safe and efficient placement of fish farming infrastructure.
- **Geographic overlap with designated fish farming zones**, aligned with national marine planning frameworks.
- **Floating foundation technology** with anchor systems that are compatible with co-located installations on the seabed or in the water column.

Based on available data, Mareld appears to meet the biological thresholds required for Atlantic salmon farming. The temperatures, salinity, and oxygen levels are within accepted welfare and growth thresholds. However, some uncertainty remains, which highlights the need for further in situ monitoring. To ensure full biological feasibility, particularly for submerged systems, it is essential to carry out prolonged on-site measurements of water current duration and oxygen saturation at various depths. These measurements will be critical for final site qualification and risk management. These conditions and characteristics position Mareld as a leading platform for pilot-scale or commercial-scale integrated aquaculture within a floating offshore wind context.

Economic Opportunity and Regional Revitalisation

As part of this study, OFFWOFF has found a robust business case for offshore aquaculture. Using Rogaland in Norway as a benchmark, the Swedish west coast has strong potential for substantial value creation and will support thousands of new jobs. Co-location enhances regional food security by enabling local salmon production in volumes ten times larger than current national consumption, reducing Sweden's dependence on imports.

The Mareld offshore fish farming concept demonstrates clear economic viability, with strong financial indicators and alignment with Sweden's broader goals for food security, marine innovation, and renewable energy integration. If implemented, it has the potential to anchor a new export-oriented industry on the Swedish west coast, with significant job and value creation. Moreover, the co-location model, combining floating wind and submerged aquaculture, positions Sweden as a pioneer in marine spatial efficiency and industrial synergy.

Environmental Impact

Regarding environmental impact, underwater noise modelling confirms that operational noise from both wind and fish farms contributes only to small local acoustic footprints around every turbine and fish farm, leading to no significant impact on the farmed fish and protected marine species during operation. With noise mitigation measures in place during installation works, such as pile driving (if needed), the impact on farmed fish and protected marine species can be heavily reduced.

Recommendations

The co-location concept could enable high-scale production of farmed salmon, potentially supporting Sweden's goal of increased self-sufficiency in seafood. This aligns with national objectives for sustainable food systems, reduced import dependency, and regional resilience.

In addition to environmental benefits, co-location could contribute to:

- **Diversifying the national aquaculture industry** with a low-carbon, high-tech model.
- **Creating jobs and innovation potential** in the coastal and offshore sectors.
- **Enhancing the overall societal value of the wind farm**, both financially and functionally.

Unlocking this potential will require:

- Targeted public and private investment
- Clear and adaptive regulatory frameworks
- Regional infrastructure and workforce development
- Continued technical validation and stakeholder engagement

Stakeholder dialogue is key to balancing innovation, ecological stewardship, and community benefit. The Mareld co-location project presents a unique opportunity to set a national example for integrated marine planning—but must be supported by proactive governance and collaborative implementation.

With these elements in place, offshore aquaculture at Mareld could serve as a blueprint for sustainable multi-use of ocean space across the Nordic region.

The Nordics as a frontrunner in multi-use ocean innovation

Multi-use of offshore space presents a unique opportunity to deliver synergies between sectors that are often planned separately. Within projects like Mareld, co-location with aquaculture can:

- Expand the long-term value proposition of offshore wind.
- Support marine biodiversity and local economies through collaborative monitoring and spatial planning.
- Enable integrated infrastructure solutions, lowering costs and reducing environmental footprints.

- Be achieved without significant underwater noise pollution, as shown in the underwater noise impact assessment.

If developed, a fish farm integrated with Mareld could represent one of the world's first deep-sea aquaculture operations within a floating offshore wind farm. This would demonstrate how multiple marine sectors can collaborate to share space, infrastructure, and environmental stewardship – setting a new standard for sustainable ocean use. It also offers an opportunity for Sweden to showcase international leadership in both offshore innovation and multifunctional marine planning.

Dissemination and Next steps

OFFWOFF has actively shared its work across different platforms. So far, dissemination includes Nordic Innovation events, innovation talks and industry seminars. We aim to continue these dialogues and reach arenas in all Nordic countries. Further steps also involve exploring opportunities for scaling the current business case and engaging in new collaborations.

Attachments

Attachments to support this report are:

- Attachment **A: Metocean Specification Report**
- Attachment **B: Hydrodynamic Analyses Report**
- Attachment **C: Underwater Noise Modelling and Impact Assessment Report**
- Attachment **D: Feasibility of Wind Farm and Fish Farm Coexistence**

A. Metocean Specification Report

Metocean Specification
Open Ocean Farming
Mareld Offshore Wind Park

Document type: **Specification**					
Title: Metocean Specification **Open Ocean Farming, Mareld wind park**					
Customer: **Internal**					
Document number: **SUB_001_SPEC**					
Code	Rev	Date	Issued by	Checked	Approved
A	1	2024-10-01	K.Strømsem	M.Lyssand	
B	2	2024-10-16	K.Strømsem	M.Lyssand	
Final	3	2025-04-12	K.Strømsem	M.Lyssand	P. Hylin

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Reference

1. Copernicus data set; GLOBAL_MULTIYEAR_PHY_001_030
2. Copernicus data set; GLOBAL_MULTIYEAR_WAV_001_032
3. Copernicus data set; NWSHELF_REANALYSIS_WAV_004_015

Revision history		
Nr	Reason for issue	Date
1	Draft for comments	2024-10-01
2	Updated draft for comments	2024-10-16

1 Objective

The wind developer Freja together with Lysekils kommun, Blue Maritime Cluster in Norway (BMC), DHI in Denmark and Subfarm in Norway will be carrying out a project financed by Nordic Innovation, OFFWOFF (OFfshore Floating Wind Open Ocean Fish Farming) to investigate

This document summarizes the underlying Metocean data to be used for the design of a SubFarm in the Mareld wind park west of Lysekil Sweden and will also be the Metocean specification for the OFFWOFF project.

Typically design data for wind, waves and current are extracted from references 1 to 3 and postprocessed into a format that can be used in design of the structures and input to do a biological assessment for the farming.

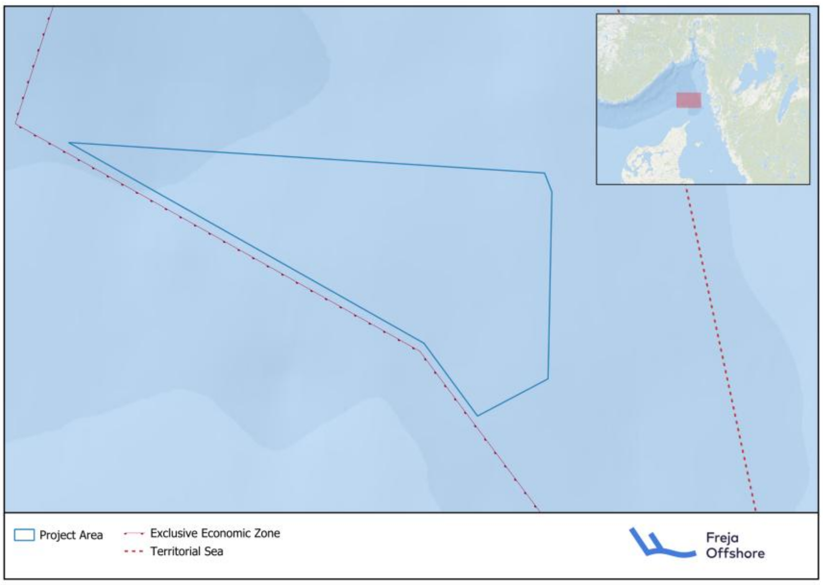
The document will be updated with new data, typically soil data and data from eventual measurements campaigns carried out. Data that will be important for design of anchor system.

Although the document can be considered a “live document” the fundamental design data presented herein will not change, only additional data will be included.

2 Introduction

Freja Offshore AB have applied for a permit to build, operate, and decommission a floating offshore wind farm called Mareld, located in the Skagerrak in the Swedish Economic Zone (SEZ), approximately 40 km west of Lysekil on the mainland of the Swedish coast (Figure 2-1). Water depths across the site range from approximately 180 m to 450 m below sea level. With an average wind speed of approximately 9.4m/s at 150 m above sea level, the Mareld area is considered to have favourable wind conditions to place a wind farm.

Figure 2-1: Mareld field location



Open Ocean Farming AS intends to apply for an offshore production licence in co-existence with the floating wind park Mareld.

This Metocean specification is established with the aim to give the necessary meteorological, biological and physical data to project to be applied to both the Wind Turbine design as well as the Farming system. At present the Wind Turbine type is not yet determined but the specifications herein can be used for any type of wind turbine. Typical areas that will be covered is:

- Hydrodynamic and structural design of the cage, feed platform, umbilical and the complete farming system as well as the offshore wind turbines
- Design and simulation of marine operations, installation of the complete system (cages, umbilicals, moorings, and feed-buoy) as well as normal farming operations as transfer of feed and energy to the feed-buoy. The same yields for the Wind Turbine design
- Simulation and design of crowding and handling of fish between the cage and the well boat/work boat
- Analysis to provide operational procedures for optimization of the fish welfare and growth (temperatures, oxygen levels, current data, turbidity and nutrition levels)
- Analysis to provide input data to be able to assess noise and other impact from the wind turbines on to the fish in the farming system.

This specification will be updated with real measured design data when available. The cage lay out is shown in Figure 2-2 and the complete system lay out in Figure 2-3. As the wind turbine for the field is not yet selected , Figure 2-4 show possible generic solutions that can be used at Mareld.

Figure 2-2: Fish Farm System Cage

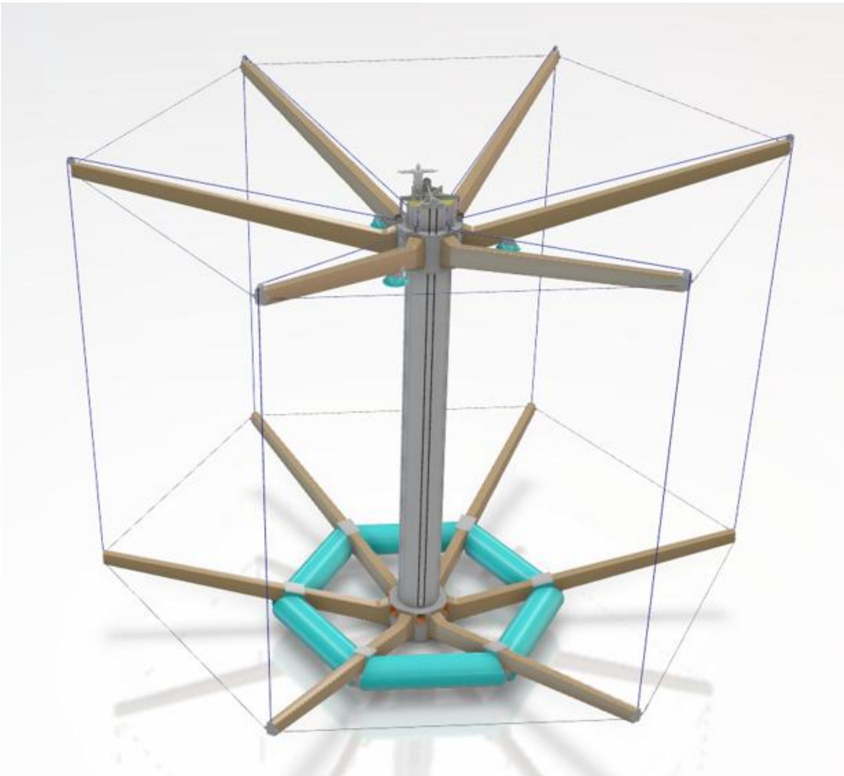


Figure 2-3: Fish Farm System, complete unit

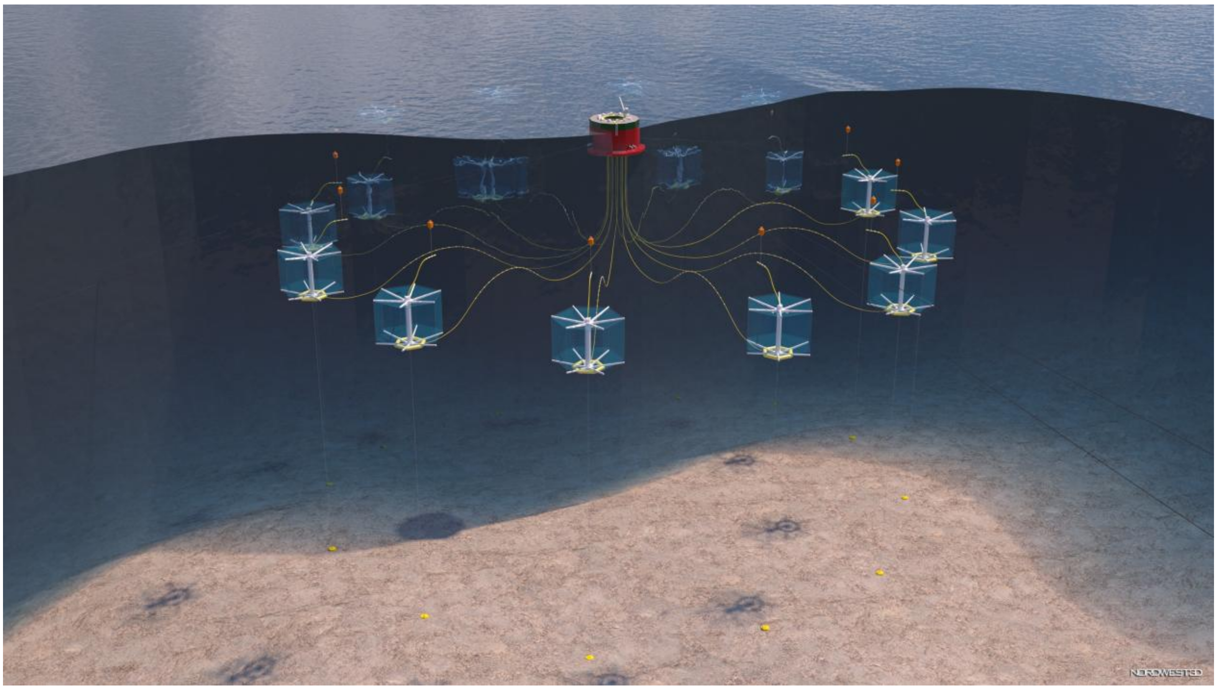
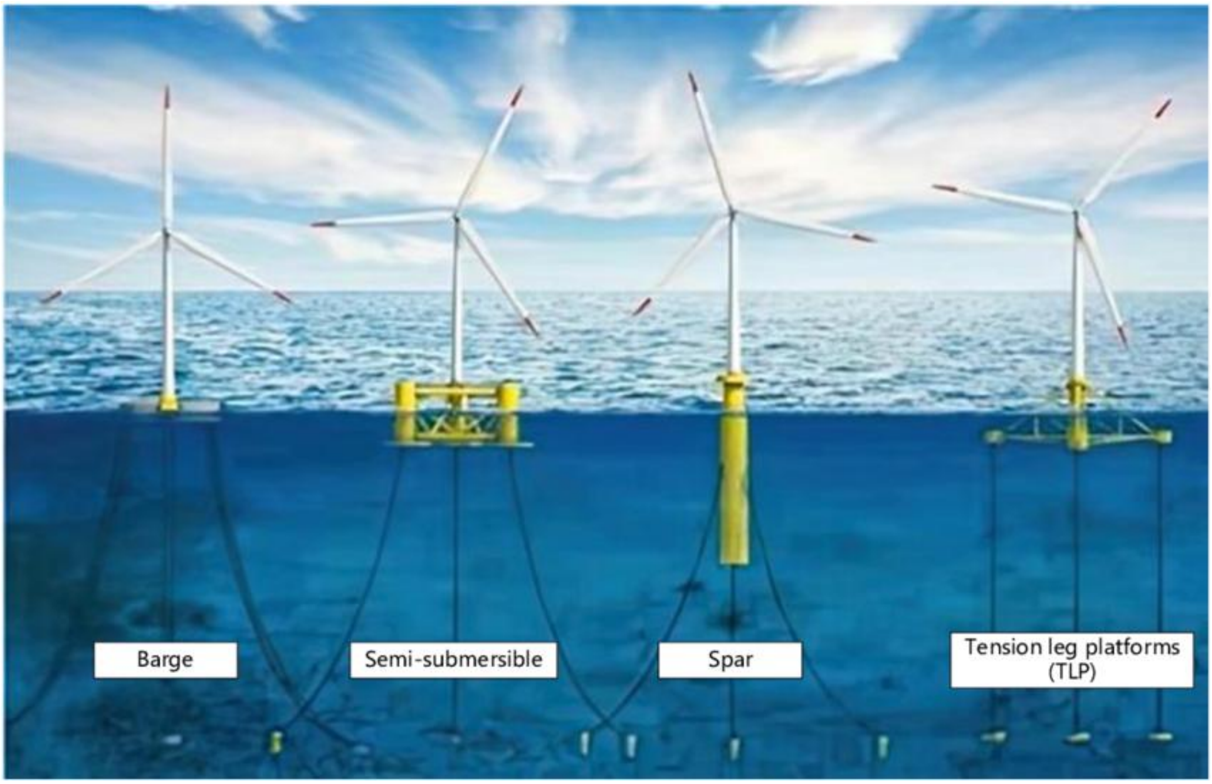


Figure 2-4: Generic type floating Wind Turbines possible solutions for Mareld



3 Location and design data

3.1 Location

The location of the Mareld field is shown in Figure 3-1. The field is located in Skagerrak approximately 45 km or 25 nm from Lysekil City in between Norway and Denmark, Figure 3-2.

Figure 3-1: Location of the Mareld field in Skagerrak

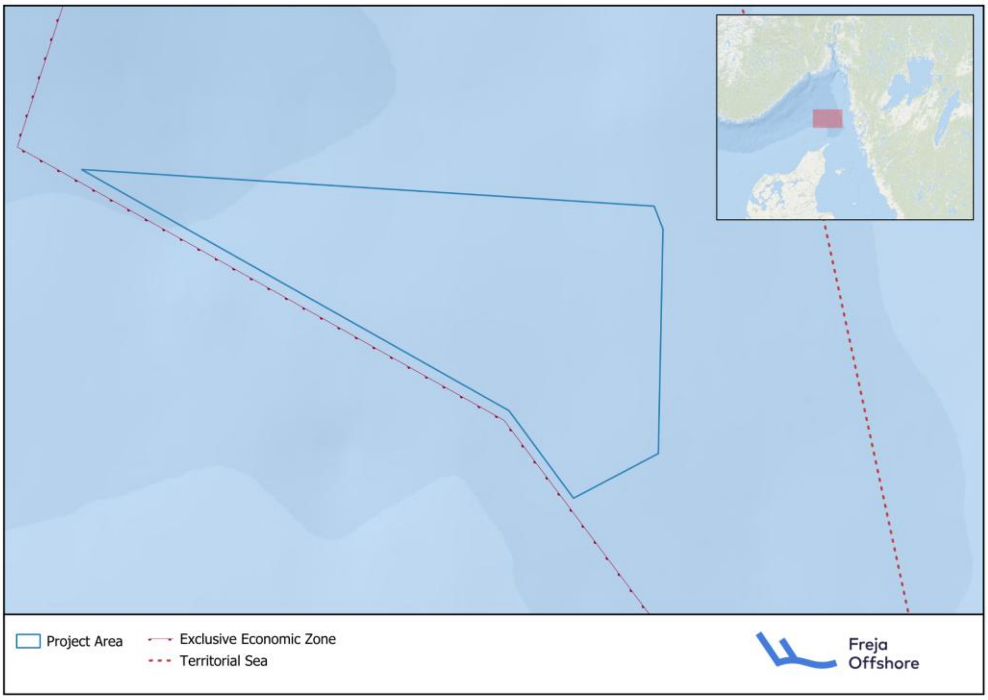
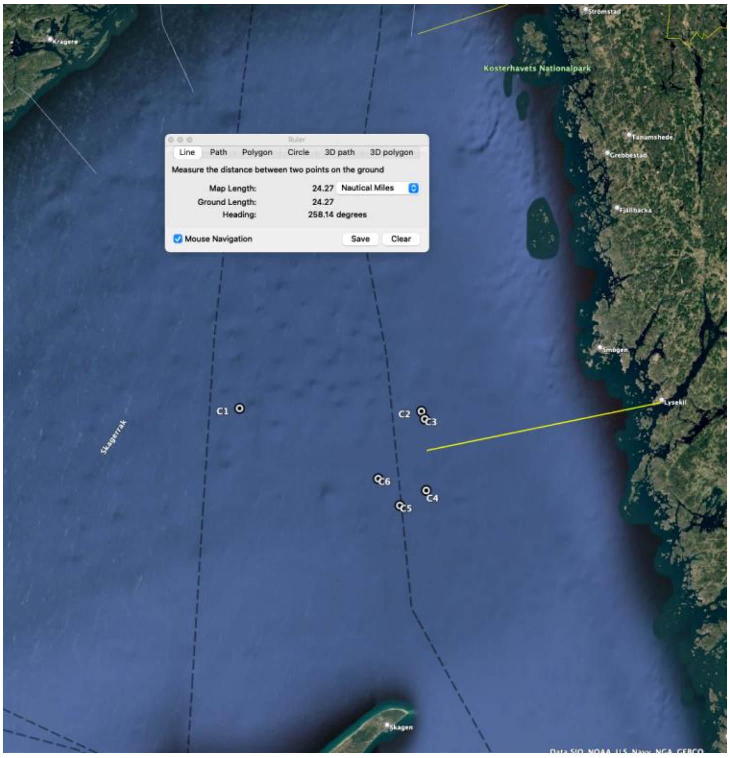


Figure 3-2: Distance to Mareld from Lysekil



The coordinates for the corners of the Mareld field is given in Table 3-1 below.

Table 3-1: Corner Coordinates for Mareld

Mareld Field Limits Coortinates				
	SWEREF99TM (m)		WGS84	
	X east	Y north	North	East
C1	212283	6467180	58.2514	10.0954
C2	246490	6464987	58.2528	10.6789
C3	247054	6463519	58.2399	10.69
C4	246739	6450142	58.1199	10.6992
C5	241654	6447548	58.0938	10.616
C6	237816	6452763	58.1382	10.5453

3.2 Depth data

The bathymetry for the area is shown in Figure 3-3 (overview) and Figure 3-4 (detailed).

Figure 3-3: Mareld Bathymetry Overview

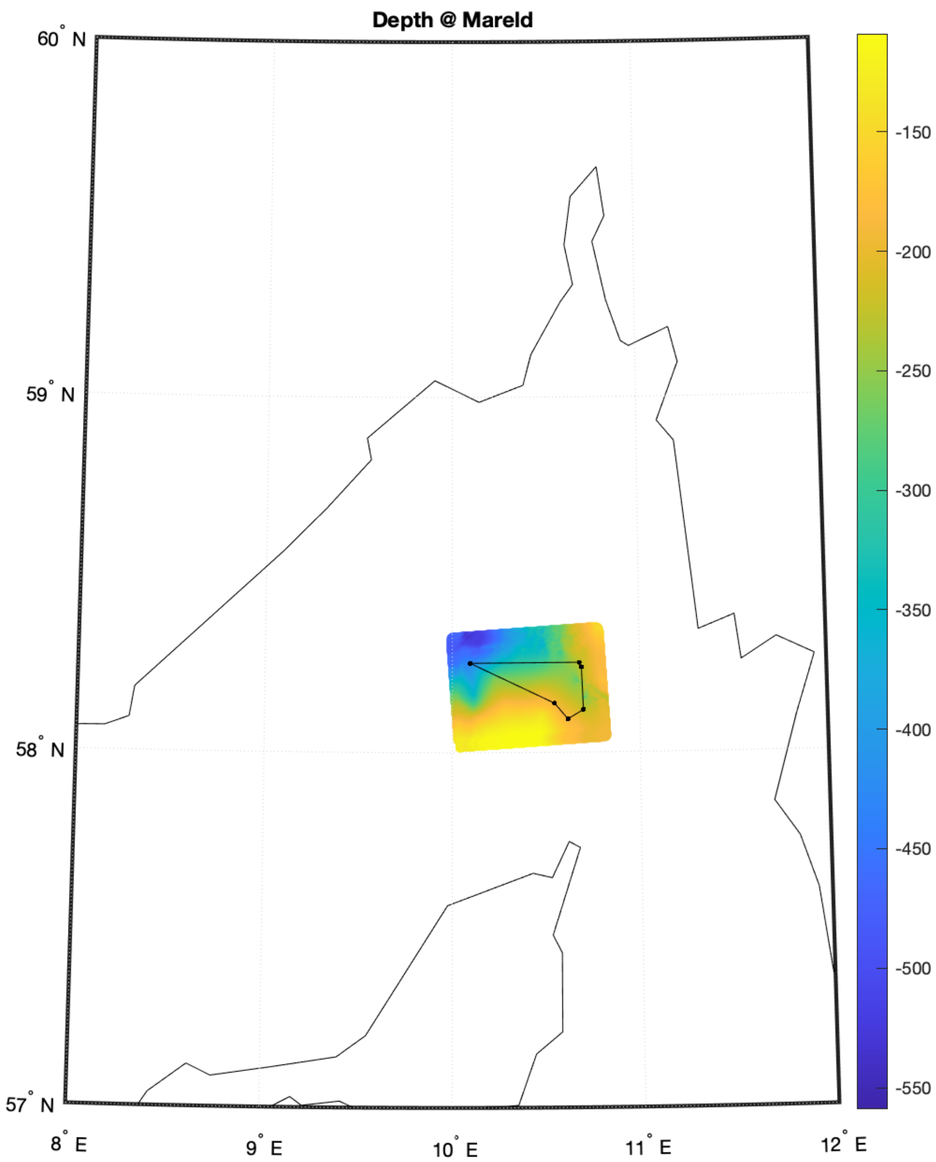
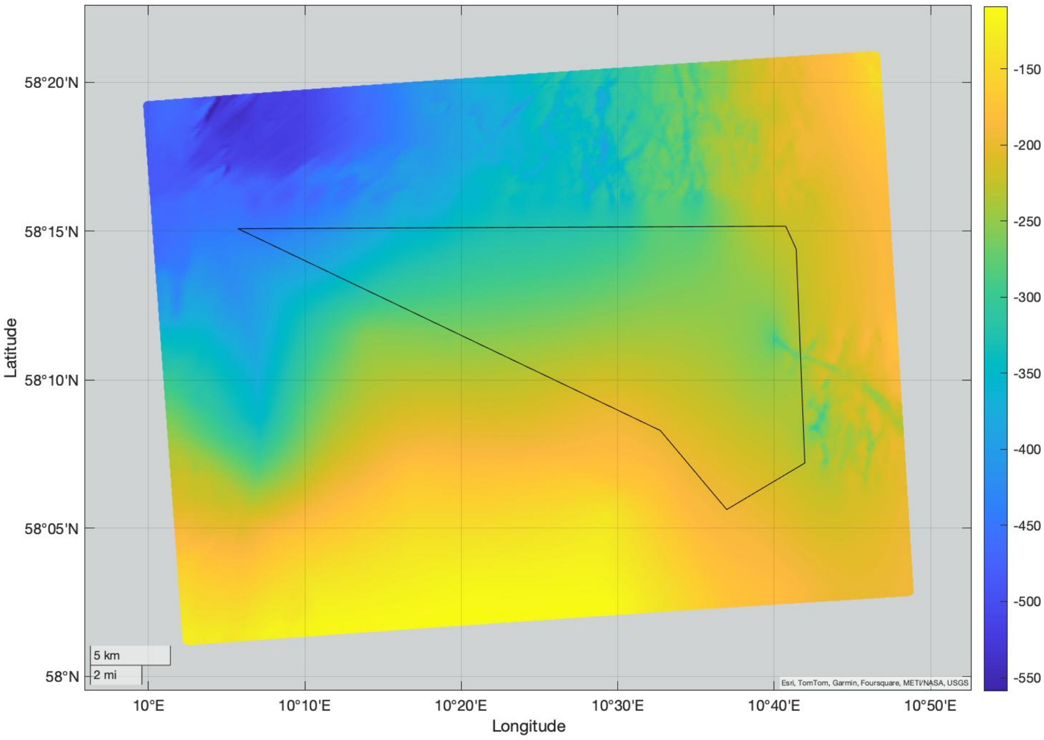


Figure 3-4: Mareld Bathymetry Detailed



The data has been provided by Mainstream in numerical format which would give correct depth contours as input to analysis and assessment.

3.3 Soil data

DHI has provided information on seabed properties we used for the noise propagation modelling as shown in Table 3-2.

Table 3-2: Seabed properties

Depth below seafloor (m)	Thickness [m]	Layer (-)	V_p [m/s]	ρ [kg/m^3]	Compressional attenuation Alfap dB/Lambda
0-15	15	Low-strength to high-strength silty clay	1550	1600	0.5
15-32	17	Medium to very high-strength clay with sand	1600	1700	0.4
32-42	10	Medium dense to very dense fine sand to silt	1625	1850	0.9
42-50	8	High to extremely high-strength clay with gravel	1700	1800	0.4
50-60	10	Limestone and sandstone	3000	2400	0.1

4 Metocean Data

4.1 Wave data

To provide wind, wave and current design data for the location we have used Open Ocean Analytics which access detailed data from the Copernicus Project

We have used the NW Shelf multiyear re-analysis data that has a resolution of.0135° × 0.0303° with data from 1980 to 1984. This covers only a part of the data required so we have also used the Global Ocean re-analysis data that has a resolution of 0.2° × 0.2° with data from 1093 to 2024 hourly.

We have extracted data for the following points, Table 4-1 below.

Table 4-1: Metocean Data Points

Metocean Data Points		
	Lat	Lon
Corner1	58.0167	10.7381
Corner2	58.1382	10.5453
Corner3	58.2514	10.0954
Corner4	58.2528	10.6788
Corner6	58.2009	10.724

Processing the and using a 3-Parameter Weibull distribution for the long term extreme significant wave gives the following extreme sea states, Table 4-2, below. Where the absolute maximum sea state is Hs = 7.3 m with a Tp = 13.3 seconds.

Table 4-2: Extreme 1, 10 and 100 year sea states

Metocean Data Points			Extreme Hs /tp		
	Lat	Lon	1 year	10 year	100 year
Corner1	58.0167	10.7381	4.9	6.2	7.1
Corner2	58.1382	10.5453	5.0	6.3	7.3
Corner3	58.2514	10.0954	4.8	6.2	7.1
Corner4	58.2528	10.6788	5.0	6.3	7.3
Corner6	58.2009	10.724	5.0	6.3	7.3
		Hs	**5.0**	**6.3**	**7.3**
		Tp	**11.6**	**12.6**	**13.3**

4.2 Current data

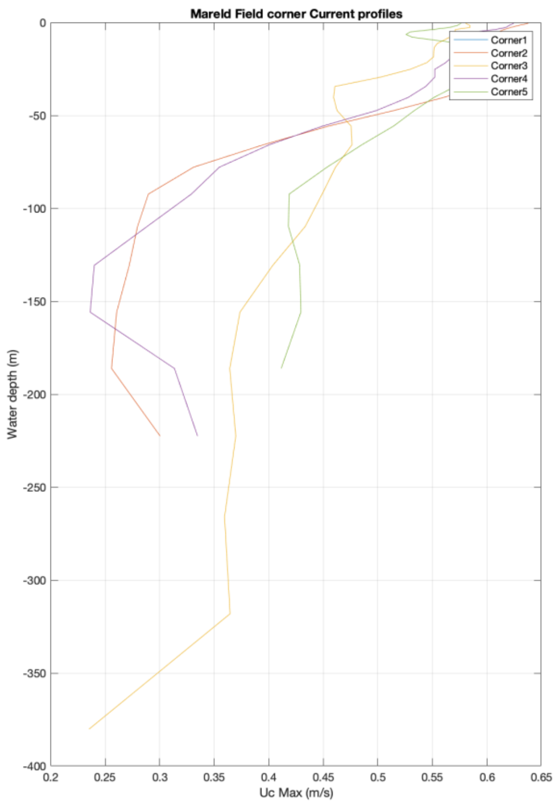
Further processing the current conditions at the corners gives the following extreme current velocities as function of depth Table 4-3 and Figure 4-1 where we see that the maximum current overall is 0.62 m/s which is at the surface.

Further detailed metocean data is found in the plots in Appendix A.

Table 4-3: Extreme Currents

Extreme Current Velocities					
Water Depth (m)	Corner1 (m/s)	Corner2 (m/s)	Corner3 (m/s)	Corner4 (m/s)	Corner6 (m/s)
Max	**0.61**	**0.64**	**0.58**	**0.62**	**0.61**
0	0.58	0.64	0.58	0.62	0.58
2	0.57	0.63	0.58	0.62	0.57
3	0.57	0.62	0.58	0.62	0.57
4	0.55	0.62	0.57	0.61	0.55
5	0.53	0.61	0.57	0.59	0.53
6	0.53	0.60	0.57	0.58	0.53
8	0.53	0.59	0.57	0.58	0.53
10	0.55	0.59	0.56	0.59	0.55
11	0.58	0.59	0.55	0.59	0.58
13	0.60	0.58	0.55	0.59	0.60
16	0.61	0.59	0.55	0.58	0.61
18	0.61	0.62	0.55	0.57	0.61
22	0.60	0.63	0.54	0.56	0.60
25	0.60	0.63	0.53	0.55	0.60
29	0.58	0.62	0.50	0.55	0.58
34	0.57	0.59	0.46	0.54	0.57
40	0.55	0.56	0.46	0.53	0.55
47	0.53	0.51	0.46	0.50	0.53
56	0.51	0.45	0.48	0.45	0.51
66	0.49	0.39	0.48	0.40	0.49
78	0.45	0.33	0.46	0.35	0.45
92	0.42	0.29	0.45	0.33	0.42
110	0.42	0.28	0.43	0.29	0.42
131	0.43	0.27	0.40	0.24	0.43
156	0.43	0.26	0.37	0.24	0.43
186	0.41	0.26	0.36	0.31	0.41
222		0.30	0.37	0.33	
266			0.36		
318			0.36		
380			0.24		

Figure 4-1: Maximum current profile



4.3 Wind conditions

4.3.1 Mean wind speed

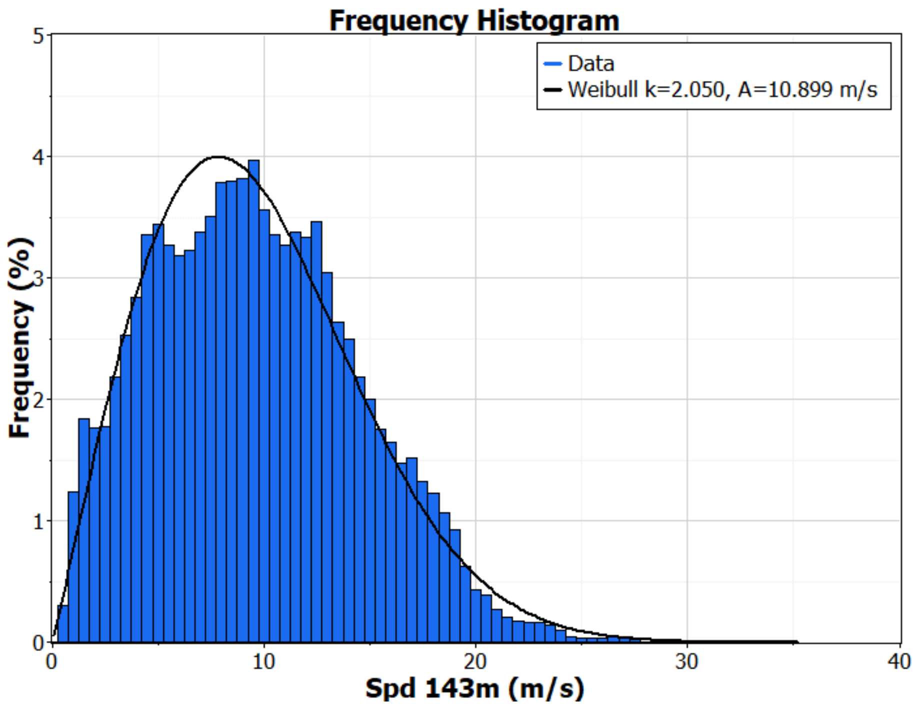
Since no on-site wind measurement data is available yet, the wind data for this project has been obtained from extrapolated modelled wind sources using industry standard methodology.

The average wind speed at 143 meters is 9.7 m/s.

This height is a typical hub height for a 15 MW turbine.

The wind speed frequency distribution for Mareld, Figure 4-2 below, captures the variability in wind speeds and the probability of occurrence of each wind speed

Figure 4-2: Frequency wind speed distribution, Mareld



The wind rose diagram (shown in Figure 4-3, illustrates the prevailing wind directions and their relative frequencies. The directional distribution of wind is key to positioning turbines to minimize wake effects and optimize energy production. The wind rose for Mareld show a strong predominance in the westerly to south-westerly direction and Figure 4-4 show the mean wind speed field at 143m

Figure 4-3: Wind Frequency Rose, Mareld

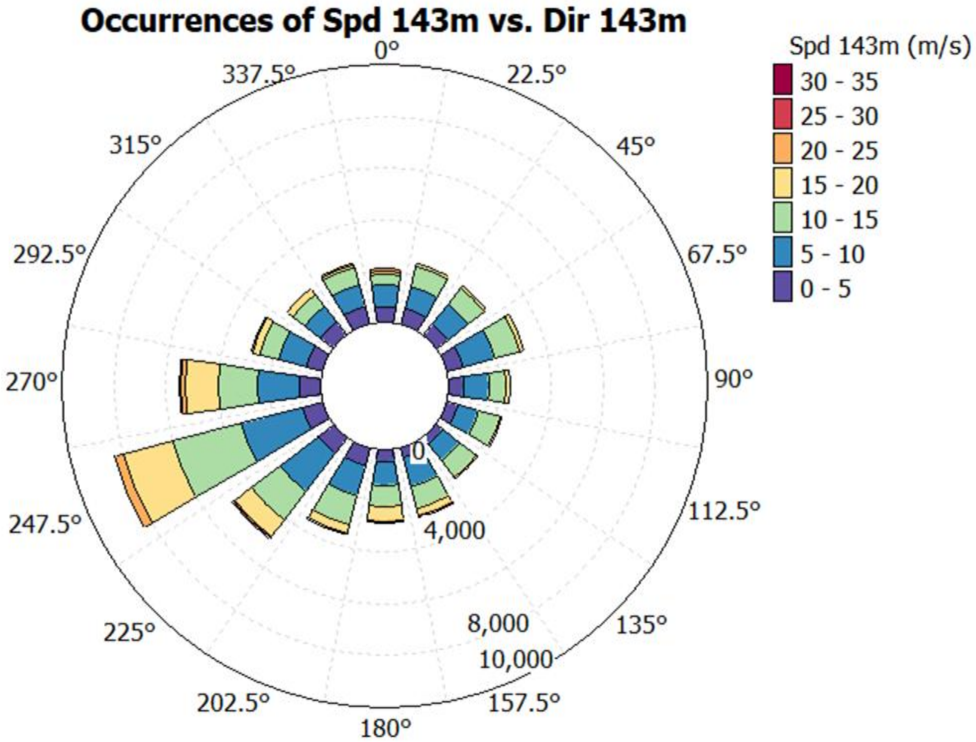
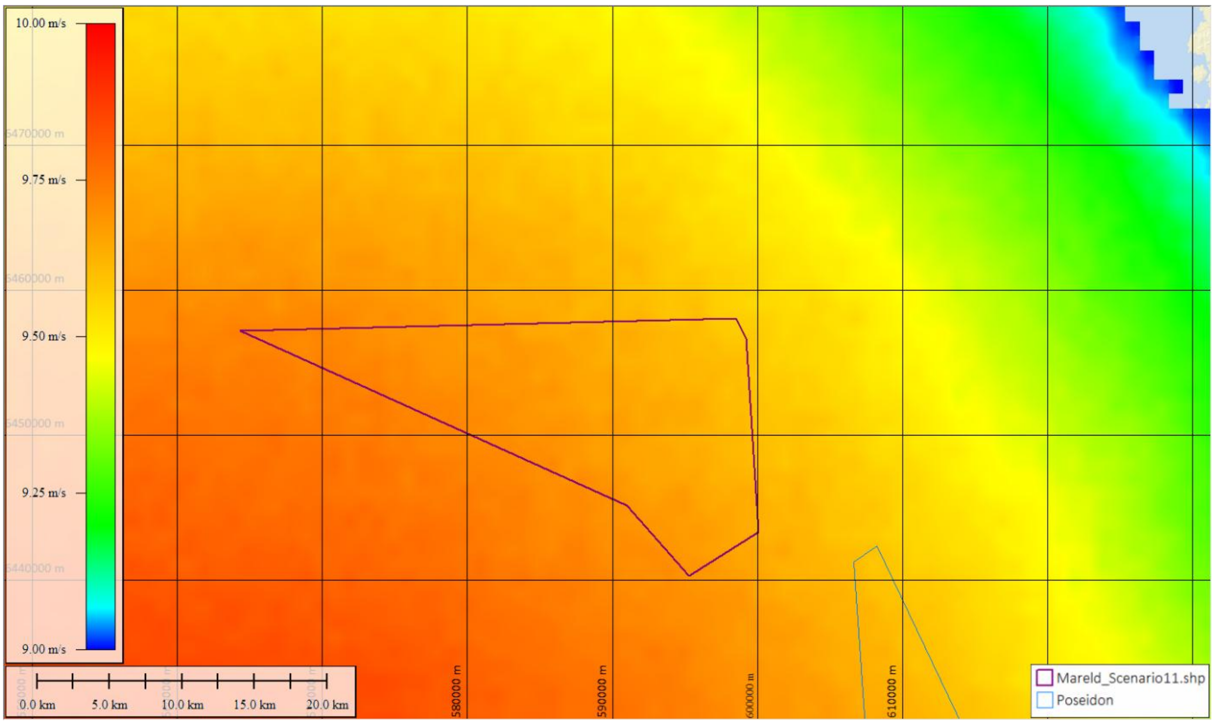
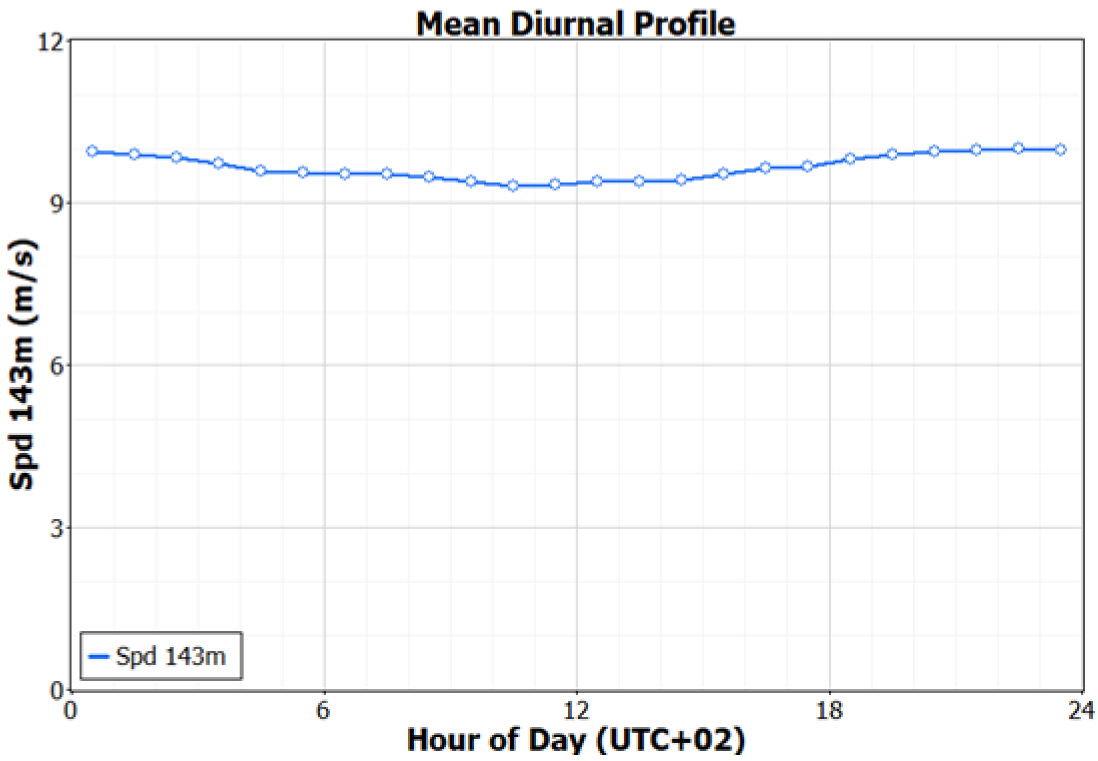


Figure 4-4: Mean speed wind field @143 m, Mareld



The mean diurnal profile of wind speed at hub height is provided in Figure 4-5. This profile offers insight into hourly variations in wind speed at the Mareld location.

Figure 4-5: Diurnal mean wind speed @ 143 m



4.3.2 Wind speed at other heights

It is normal to give design wind speed as 10 min mean at z = 10 meters so to transfer the wind speed to other heights by using the standard function with height given below.

$$U(z) = \overline{U(z)}_{ref,10min} \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Where:

- U(z) : Wind speed at height z
- $\bar{U}(z)_{ref,10min}$: Reference 10 min mean wind speed at reference height
- z : The desired height of wind speed transferred
- z_{ref} : The reference height of the given wind speed
- **α** : Wind shear exponent depending on surface roughness
    - open sea
    - 0.14 flat open terrain (e.g. grassland)
    - 0.25 for forests
    - 0.40 for urban areas

Appendix A. Metocean Data Figures

The figures, Figure 4-6 and Figure 4-7 overleaf, summarise the Metocean data for the location.

Figure 4-6: Summary of data (Physical and biological) for Corner 1

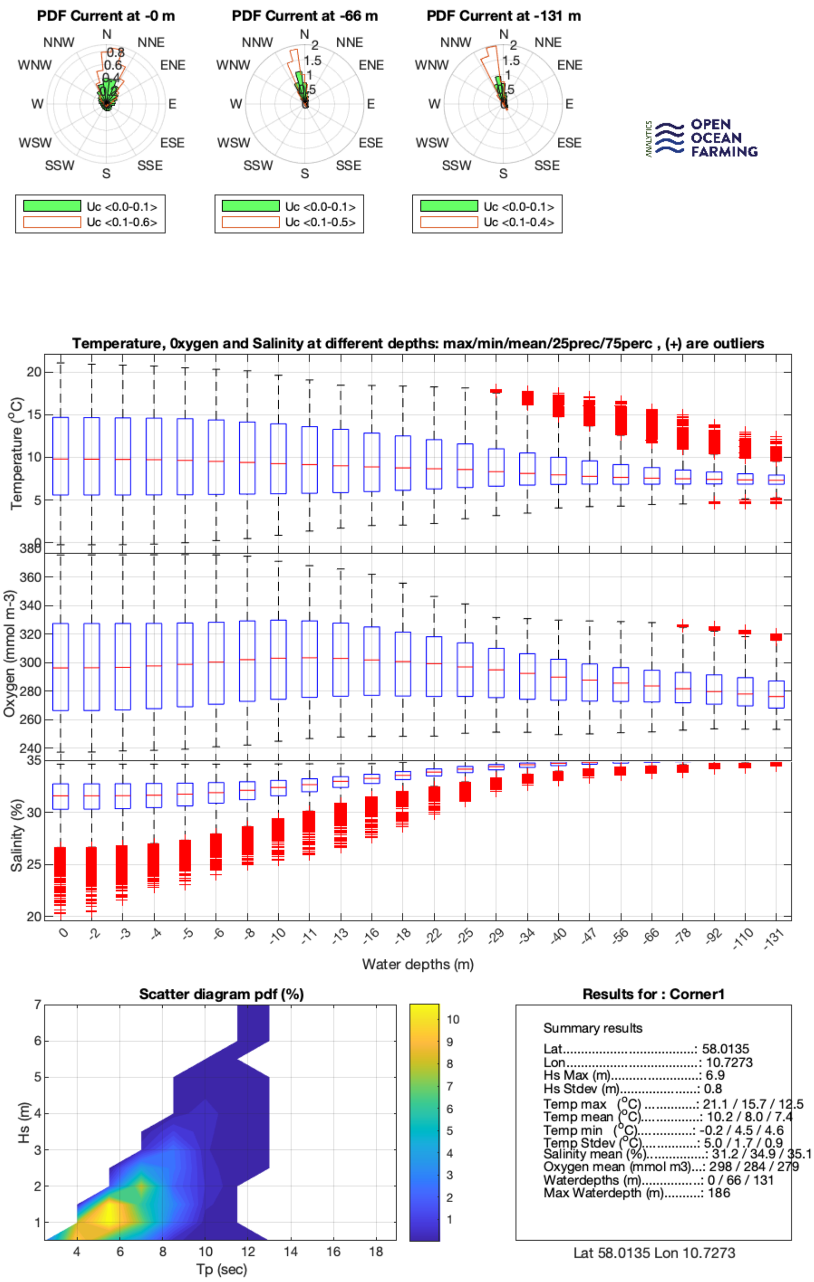


Figure 4-7: Summary of data (current) for Corner 1

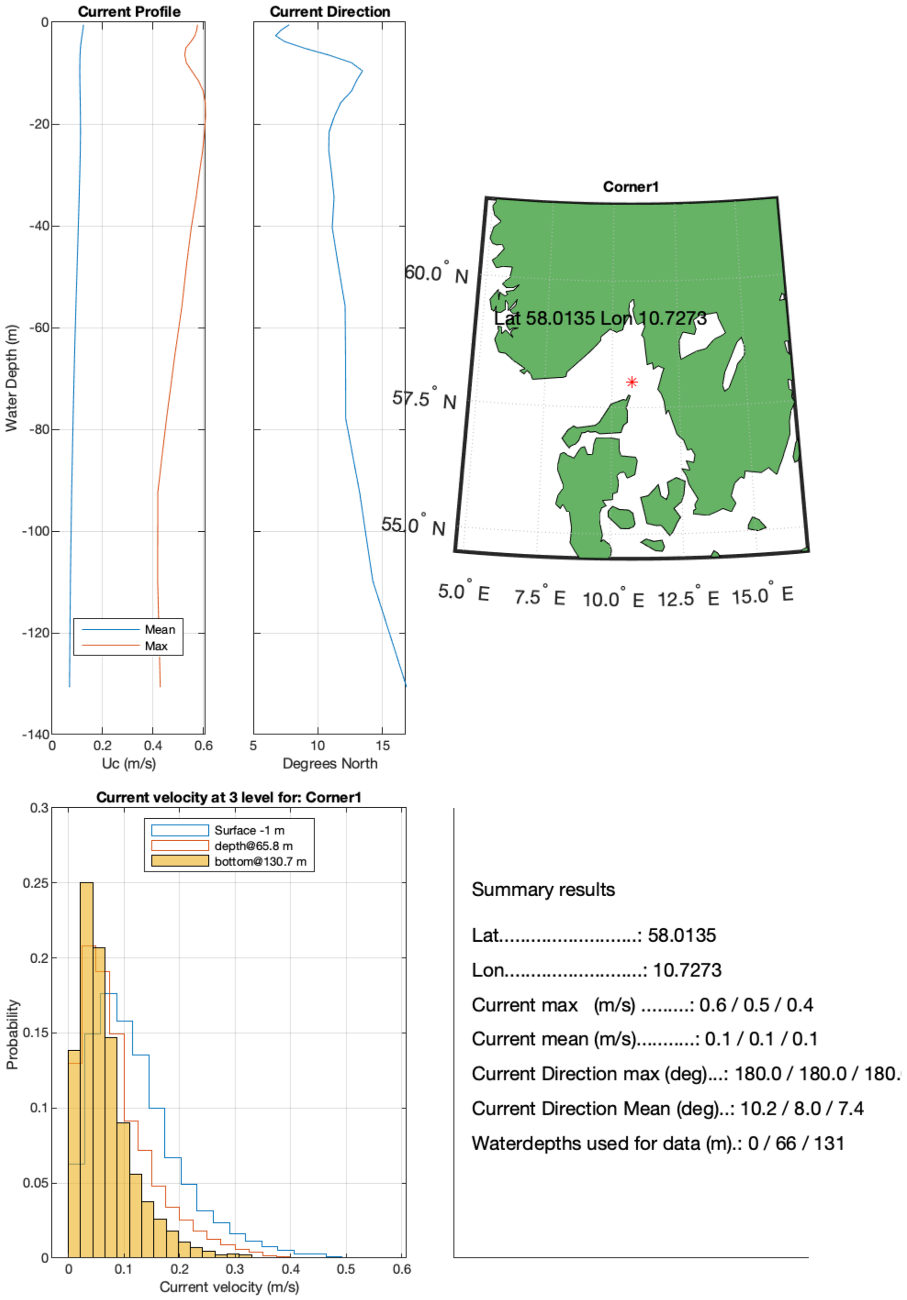


Figure 4-8:Summary of data (Physical and biological) for Corner 2

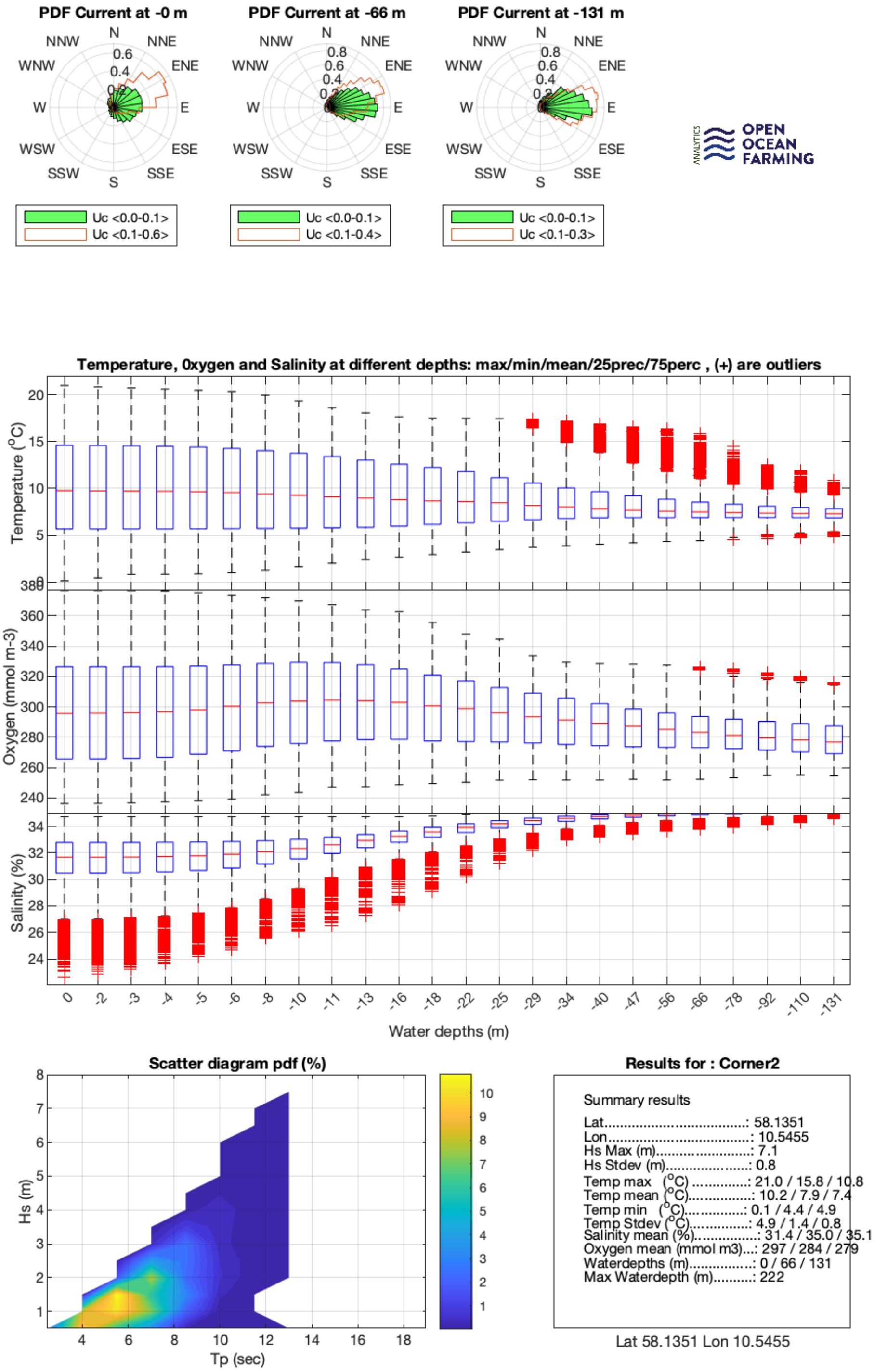


Figure 4-9: Summary of data (current) for Corner 2

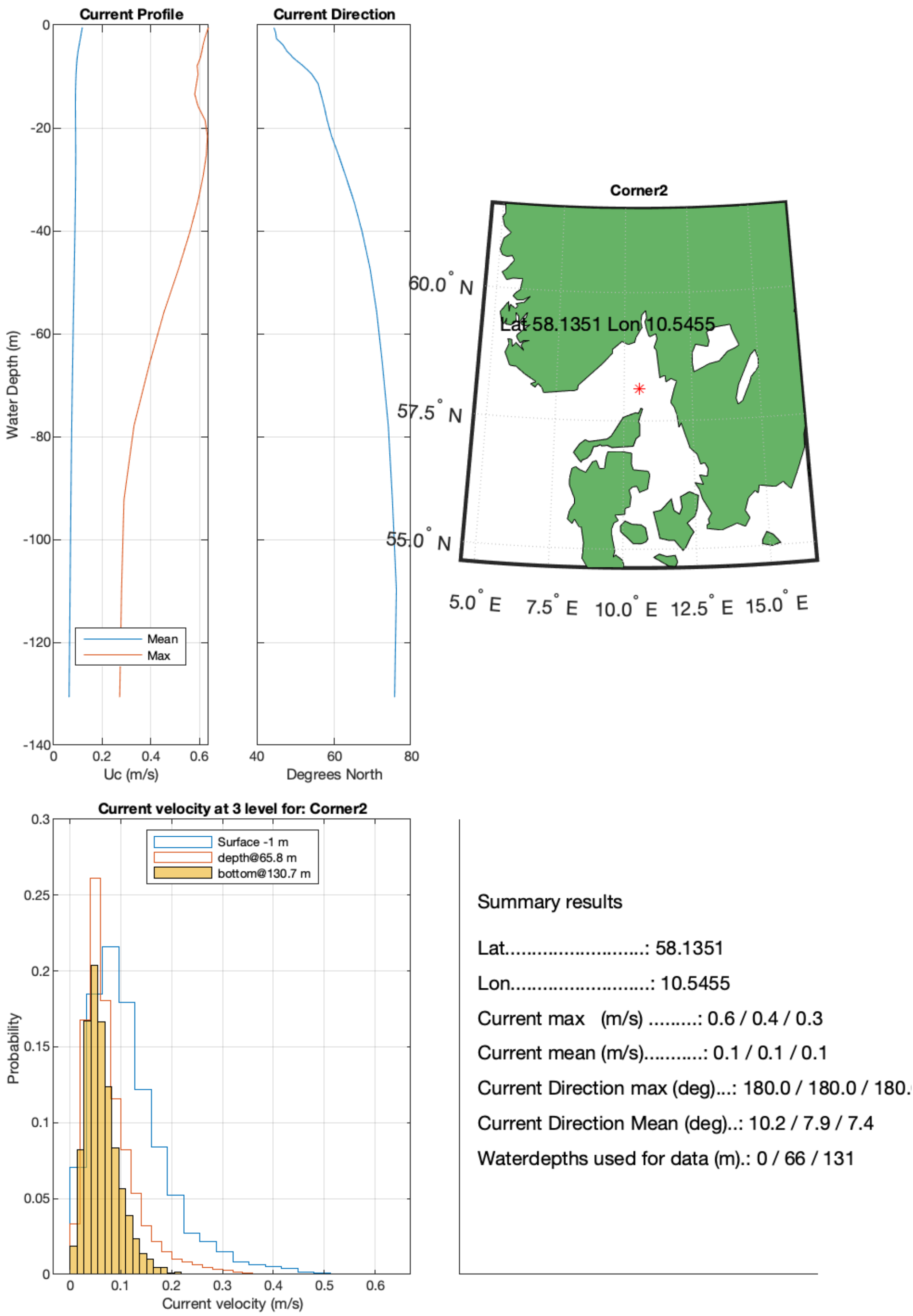


Figure 4-10: Summary of data (Physical and biological) for Corner 3

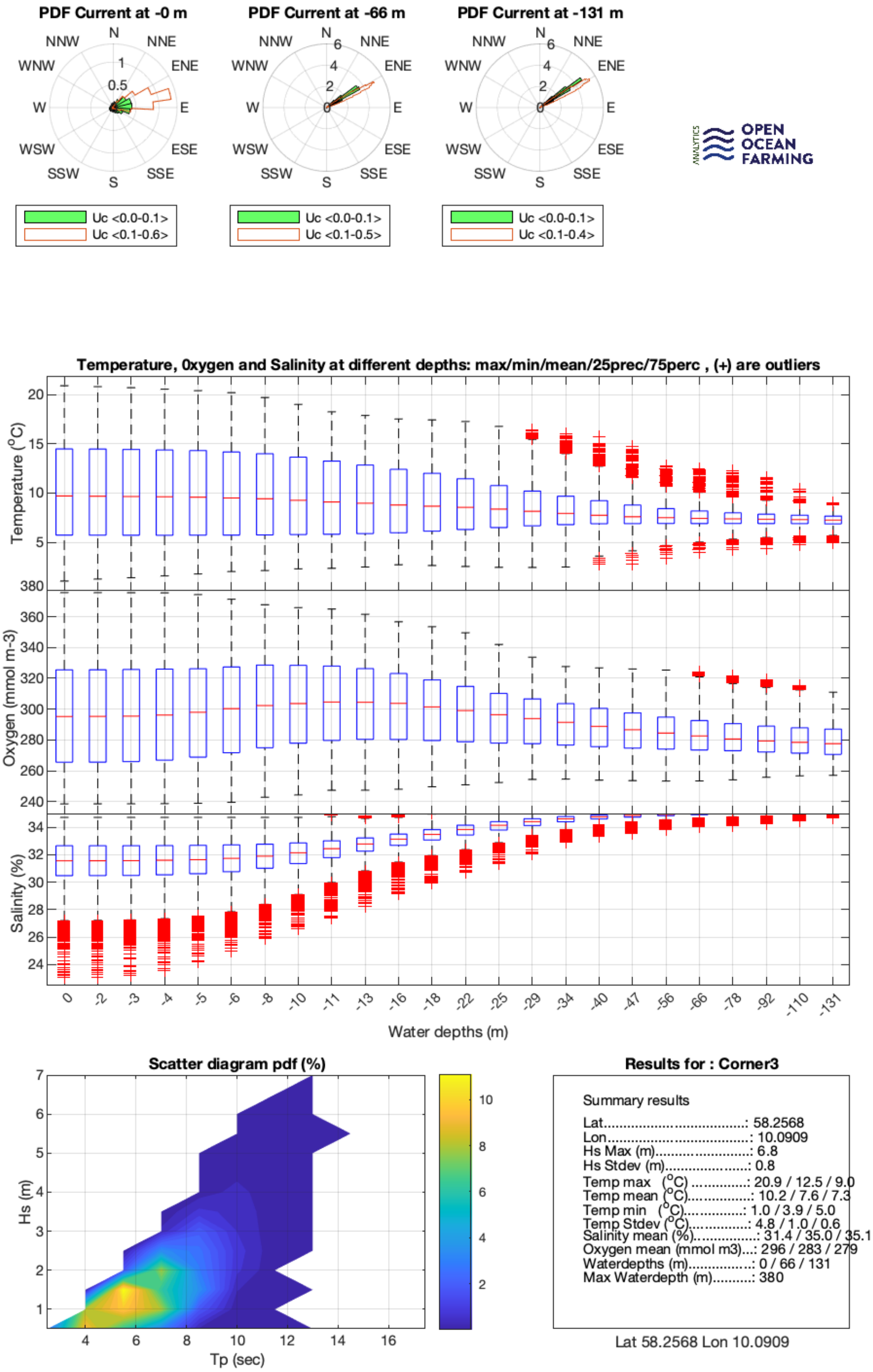


Figure 4-11: Summary of data (current) for Corner 3

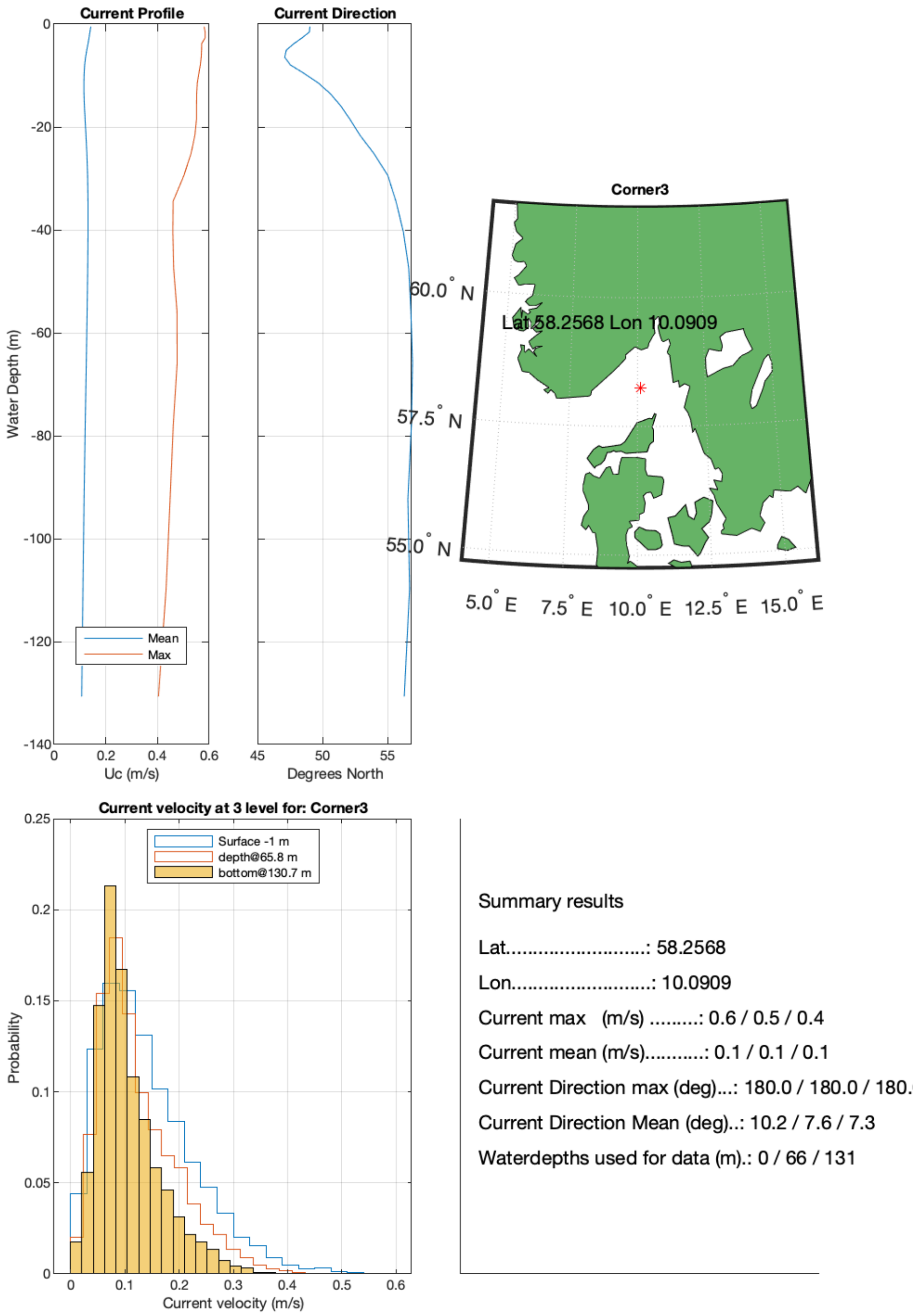


Figure 4-12: Summary of data (Physical and biological) for Corner 4

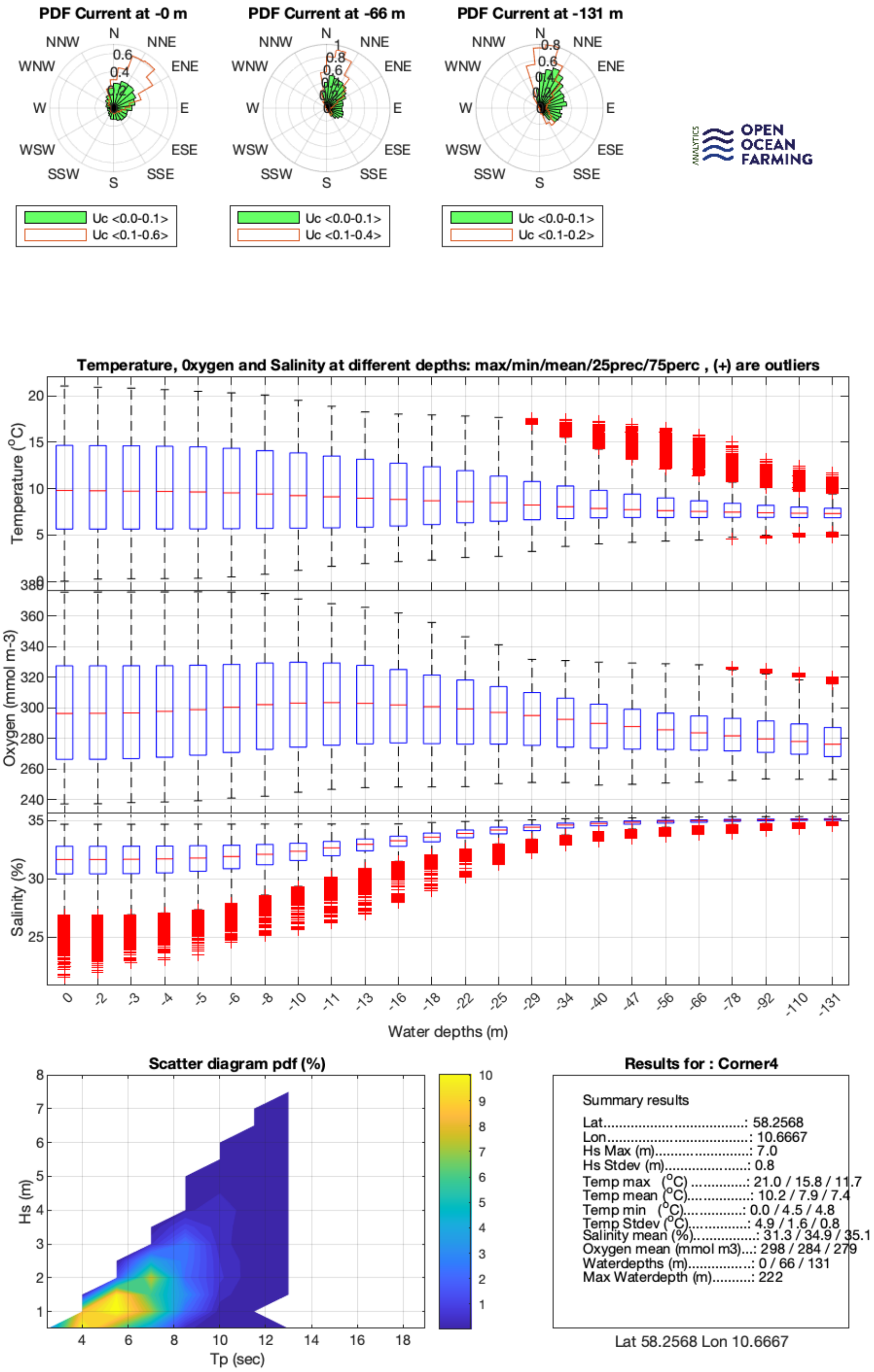


Figure 4-13: Summary of data (current) for Corner 4

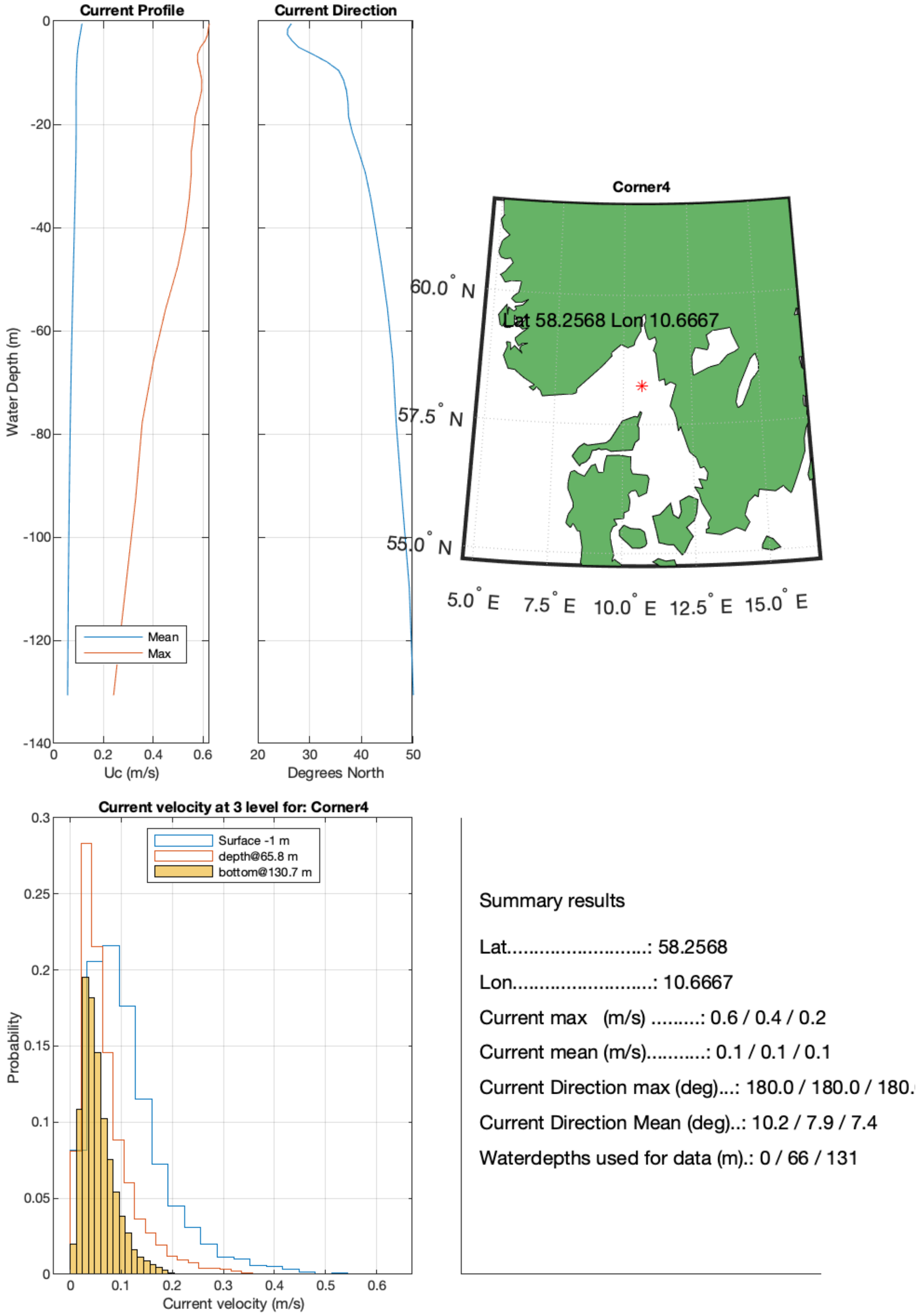


Figure 4-14: Summary of data (Physical and biological) for Corner 5

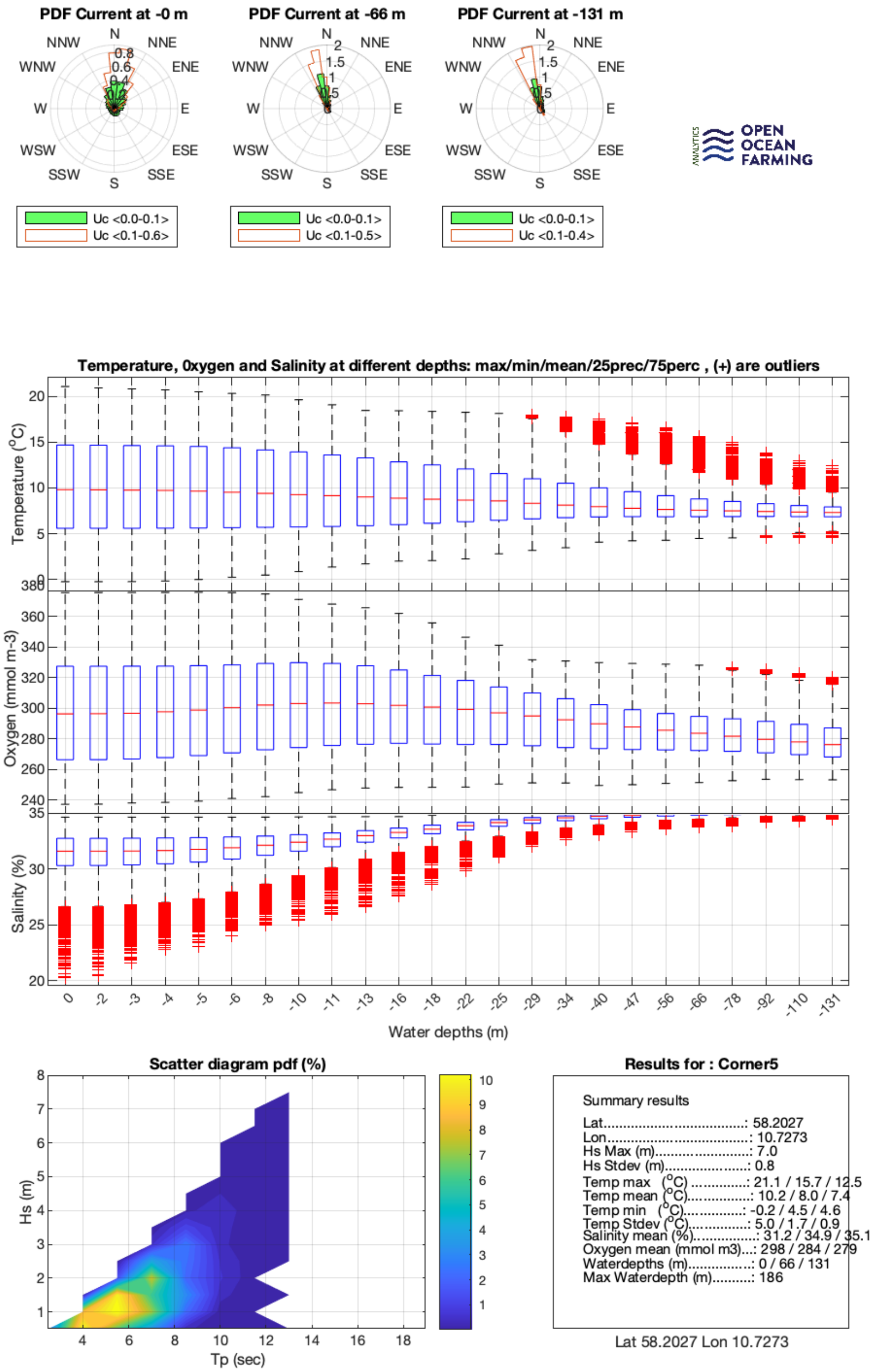
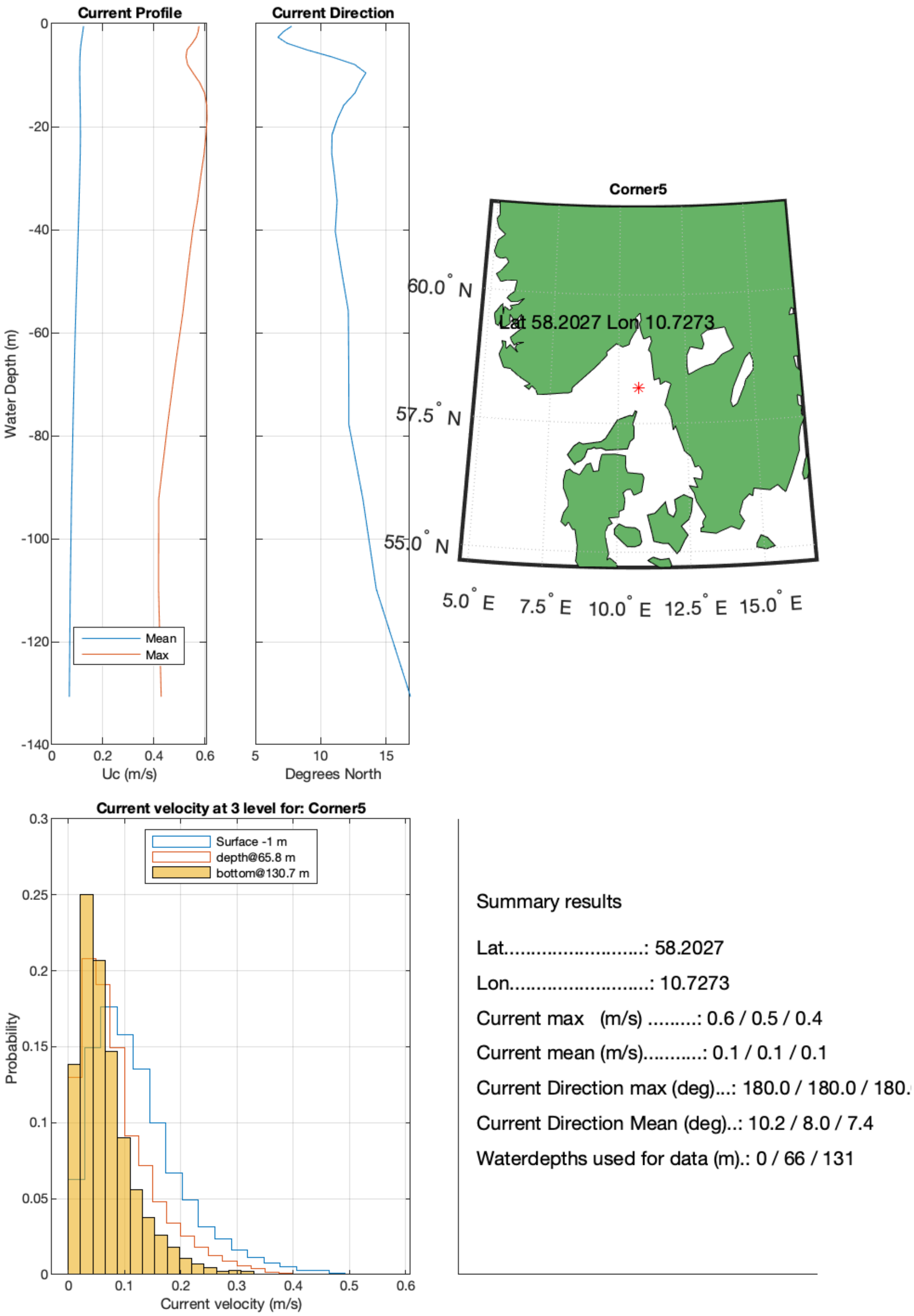


Figure 4-15: Summary of data (current) for Corner 5



B. Hydrodynamic Analyses Report

OFFWOFF Project

Hydrodynamic Analysis Report
Open Ocean Farming
Mareld Offshore Wind Park

Document type: **Analysis Report**					
Title: Hydrodynamic Analysis Report Open Ocean Farming Mareld Offshore Wind Park					
Customer: **Internal**					
Document number: **SUB_001_REP**					
Code	Rev	Date	Issued by	Checked	Approved
A	1	2025-03-20	K.Strømsem	M.Lyssand	
B	0	2025-05-16	K.Strømsem	Mainstream	M.Lyssand

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References

1. SUB_001_Spec: Metocean Specification Open Ocean Farming, Mareld wind park.

Revision history		
Nr	Reason for issue	Date
1	Draft for comments	2025-03-23
2	Final with modifications for comments implemented	2025-05-16

1 Executive summary

The dynamic analysis of the Subfarm and the two different wind turbines, one semi-submersible 15 MW turbine and one Spar buoy 5 MW turbine, confirms that Subfarm can co-exist within an offshore wind farm.

The reason for using a small and a larger wind turbine is to assess if there is a huge difference in the offset/performance and the motions that give input to DHIs noise calculations.

Performance data for all units show acceptable levels of motions, power production and loads. The use of taut mooring applying ropes of Feed barge for the Subfarm display very high pretensions. However, the final solution of the mooring system for the Feed Barge will be using heavy chains which will minimize the pre-tensions but keep the motions of the within acceptable watch-circles.

Furthermore, the analysis in this report is also used to derive data from the various mooring systems to DHI to allow them to perform the noise analysis to as input to the questions related to fish(farming) and noise. The noise calculations and results are shown in the DHI report.

It should be noted that no optimization of the mooring systems has been performed, and the data is based on the initial assumed dimensions and sizes as no specific solution for the wind turbines has been selected for Mareld we have based the results on the generic types of wind turbines that has been established by Orcina and is a part of OrcaFlex.

For the operating extreme conditions with intact mooring systems the offsets and motions of the wind turbines and the fish farm elements is demonstrated to be small and ensures that no physical interactions between the different objects occur.

However, to fulfil the design requirements for accidental load cases the systems must be able to accommodate 1 and 2 mooring line loss.

The cages in the Subfarm uses the umbilical as a secondary mooring hence a mooring line break will only let the cage float to the surface and be pulled back to the feed barge. A mooring line loss of the feed barge will increase the offset of the feed barge slightly but as the feed barge have three mooring lines in each group the feed barge will maintain position within the existing perimeter marked by the cages.

The implications for the wind turbines will be that for the wind turbines close to the fish farm(s) the mooring lines pointing away from the fish farm needs to have a group of mooring lines with at least 3 lines in the group. The impact on the wind farm is therefore minimal and the cost of these eventual few extra lines (in caser the turbine by design) has less than 3 lines in the group, will be negligible.

2 Objective

The wind developer Freja together with Lysekils kommun, Blue Maritime Cluster in Norway (BMC), DHI in Denmark and Subfarm in Norway will be carrying out a project financed by Nordic Innovation, OFFWOFF (OFfshore Floating Wind Open Ocean Fish Farming) to investigate

This document describes the dynamic analysis of a SubFarm co-located with two different types of offshore floating wind turbines for Metocean conditions given for the Mareld wind park west of Lysekil Sweden.

The purpose of the analysis herein is two-fold:

1. Is to provide data for DHI to be used in evaluating the noise from the windfarms and the aquaculture system and,
2. To provide data on offset and motions of typical wind turbines in combination with the Subfarm to assess if these concepts can co-exist in the same marine space.

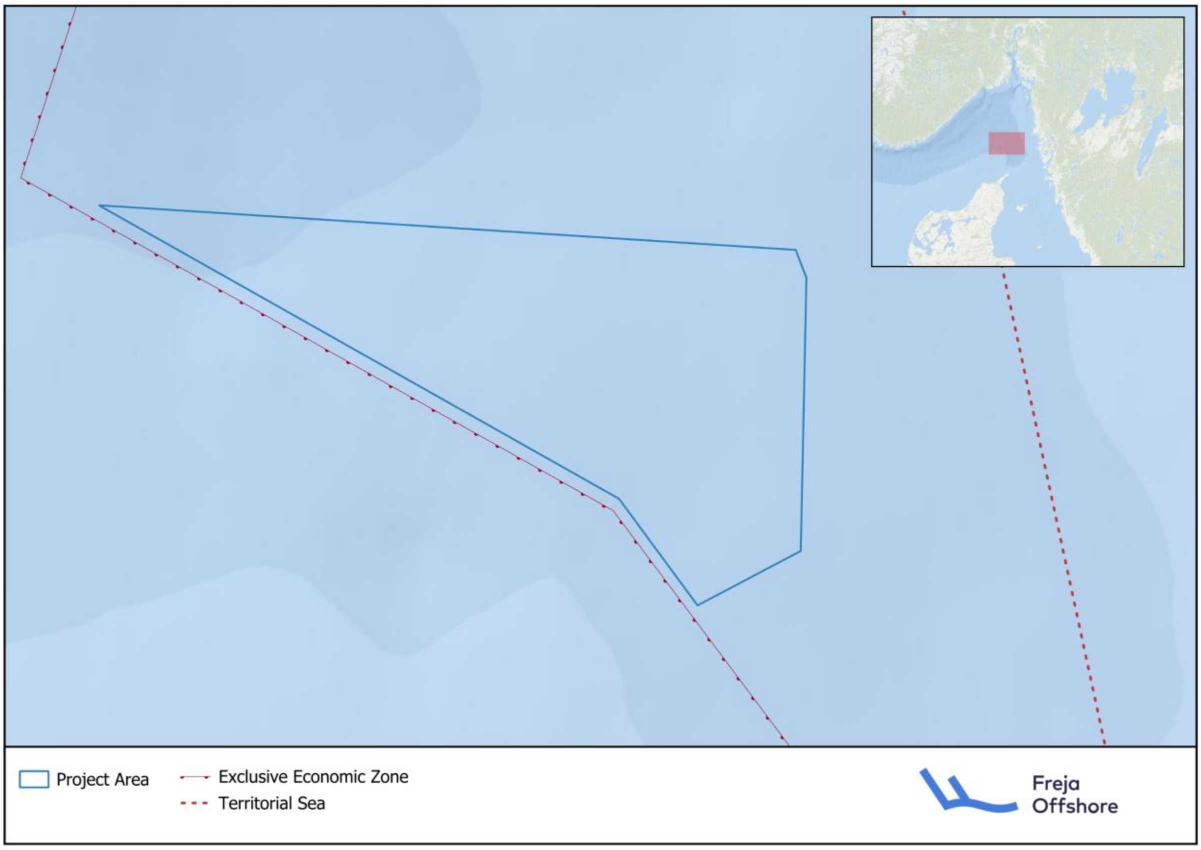
The document will summarise the basic design data for the systems that is modelled and analysed as well as give some overall details related to the aquaculture system and wind turbine systems.

Finally, a summary of results and conclusions related to the co-existence from a hydrodynamic point of view.

3 Introduction

Freja Offshore AB have applied for a permit to build, operate, and decommission a floating offshore wind farm called Mareld, located in the Skagerrak in the Swedish Economic Zone (SEZ), approximately 40 km west of Lysekil on the mainland of the Swedish coast, Figure 3-1. Water depths across the site range from approximately 180 m to 450 m below sea level. With an average wind speed of approximately 9.4m/s at 150 m above sea level, the Mareld area is considered to have favourable wind conditions to place a wind farm.

Figure 3-1: Mareld field location



Open Ocean Farming AS intends to apply for an offshore production licence in co-existence with the floating wind park Mareld. The Open Ocean Farming system is shown in Figure 3-2 and Figure 3-3 The floating wind turbine system to be used for Mareld is not yet determined but potential turbine systems are shown in Figure 3-4,

Figure 3-2: Fish Farm System Cage

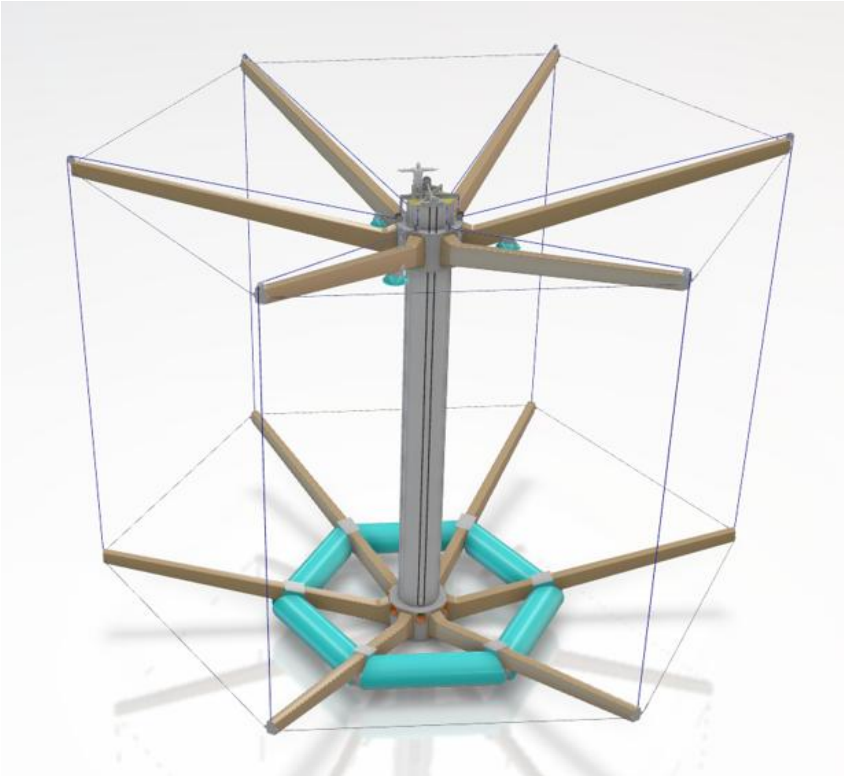


Figure 3-3: Fish Farm System, complete unit

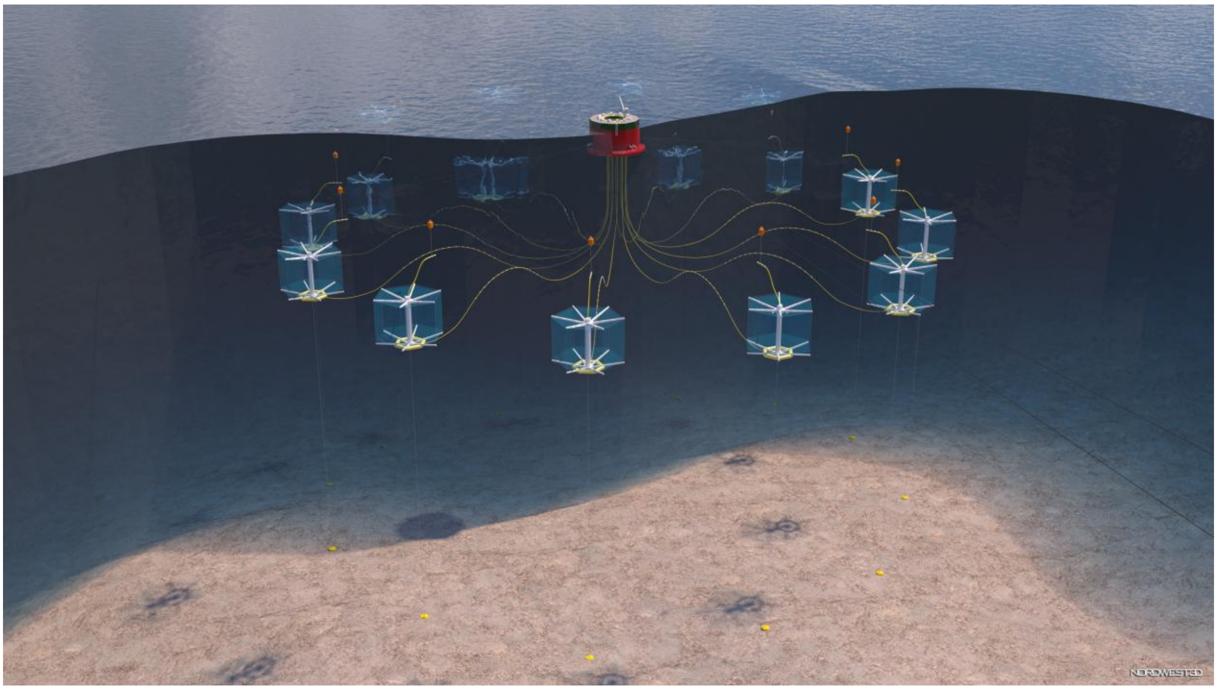
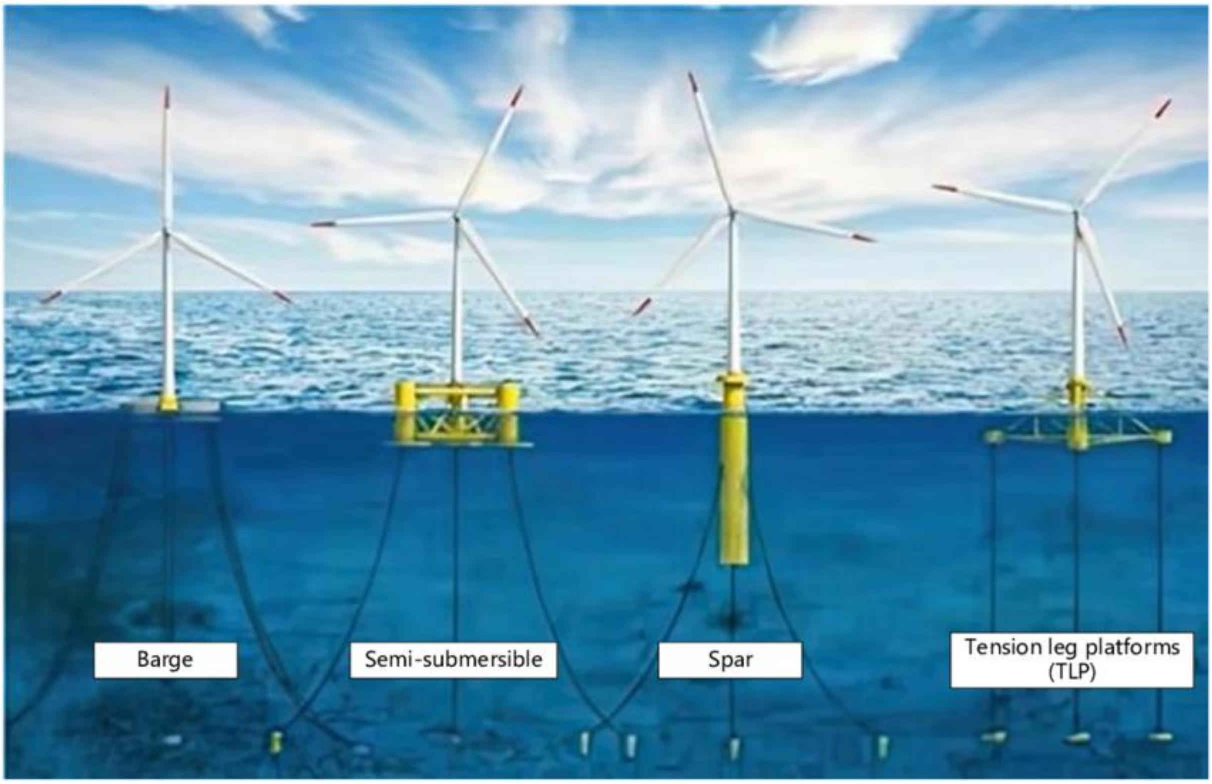


Figure 3-4: Generic type floating Wind Turbines possible solutions for Mareld



However, for this work herein, we will analyse two of the most probable solutions namely a Semi-submersible (OrcaFlex model shown in Figure 3-5) and a Spar (OrcaFlex model shown in Figure 3-6). For simplicity and speed, we are using the wind turbine models that is included in OrcaFlex, modelled by Orcina, with mooring systems modified to the proper water depth.

On models a 5 MW turbine and one models a 15 MW turbine, and this will give a range in the performance and allow us to assess if there are substantial differences for motions between a large and small wind turbine. This will in turn will give input to the noise assessment by DHI which then can show if there are substantial differences between small and large wind turbines related to noise.

These two wind turbine model will be analysed together with the Subfarm system Figure 3-7.

Figure 3-5: Semi-submersible Wind Turbine

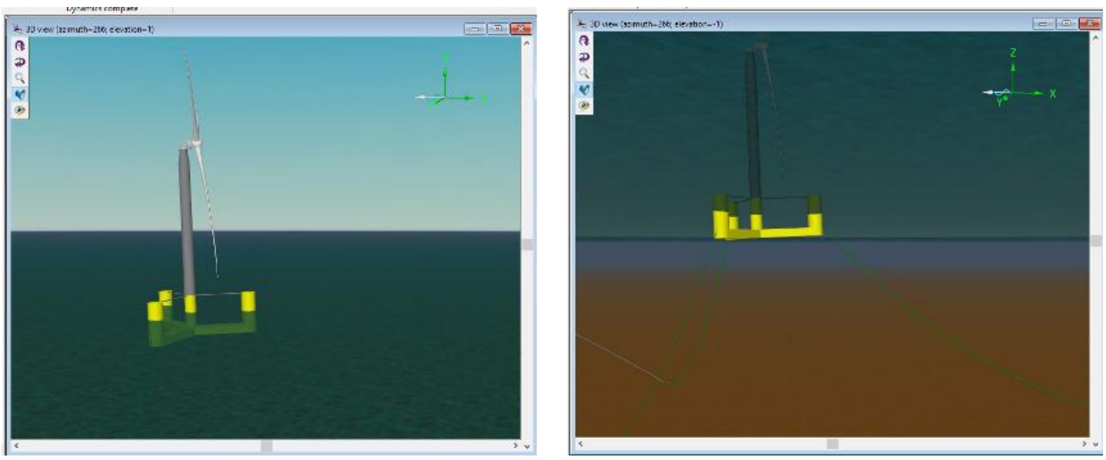


Figure 3-6: Spar Wind Turbine

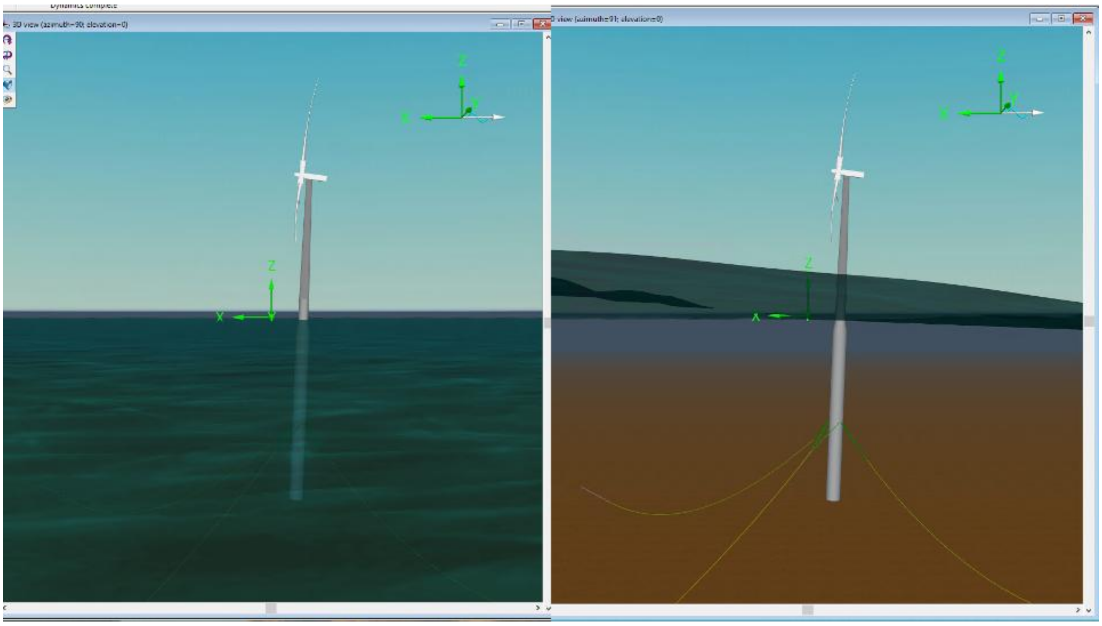
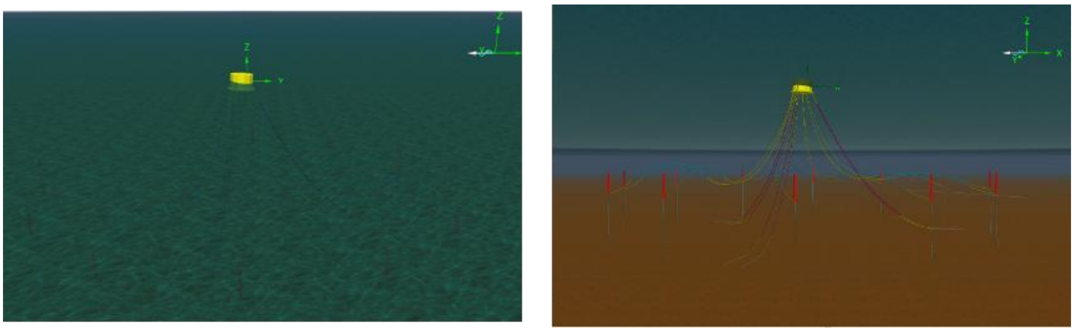


Figure 3-7: Subfarm Fish Farm



In the Subfarm system the actual cages are shown as “red sticks” which reflects that the actual cage model is a very complicated and heavy model to run which for the analysis for co-location is not required. Therefore, we have instead replaced the actual cage model with an equivalent hydrodynamic model represented by a 6 DOF buoy, but that has the same hydrodynamic properties as the original cage.

4 Modelling

For this analysis we have selected the actual water depth as 200 meters. The wind turbines are generic models that is developed by Orcina LTD and is a part of the available models in OrcaFlex. We have reviewed the models and checked their dynamic performance, and they seem adequate to be used to assess co-existence and input to noise.

4.1 Metocean

The metocean conditions used is the 100-year omni-directional condition with Hs = 7.3 m, Tp = 13.3 s and a maximum current speed though the whole water column of 0.62 m/s which we have combined with an average wind speed at 143 meters of 9.7 m/s. The design sea state is defined in the OFFWOFF metocean specification delivered as a part of the project.

4.2 Spar Wind Turbine

The Spar wind turbine has a total structural length of 130 meters with the Nacelle some 100 meters above the sea surface. Total weight is around 7500 tonnes. The blade lengths are round 62 meters, and the total power rating is 5 MW.

The turbine is moored using spread 3-leg system with wires and chains. The cains are of a stud-link type with a bar diameter of 50 mm and a weight of 78 kg/m. The type of chain and weight are given as it may be an important input to the noise assessment.

The mooring lines is connected some 550 meters from the wind turbine; hence each wind turbine covers a circular area of approximately 0.9 km^2.

4.3 Semi-submersible Wind Turbine

The semi-submersible wind turbine has a total structural mass around 20 000 tons. The tower and nacelle height above the mean sea level is 130 meters and the blades are around 120 meters long. The rating of the wind turbine is 15 MW.

The platform is moored with a 3-leg spread mooring system with stud-link chain with approximately 700 kg/m weight.

The anchor points are approximately 830 meters from the center of the platform; hence each wind turbine covers a circular area of approximately 2.2 km2.

4.4 Subfarm Fish farm

The Subfarm fish farm consists of a central feed buoy with a weight of approximately 4400 tons, and 12 submerged cages 60 tons each. The feed buoy is a designed developed by Sevan SSP and is built on their circular platform concept. This specific feed barge design is built on their design for a wind farm substation. This design is verified by model testing at Stadt Towing Tank.

Each cage is connected directly to the seabed via a winch and a wire, and the depth can be varied depending on the requirements from the fish. In addition, each cage has an armed umbilical to the feed platform providing feed, communication, air to the cage and acting as a secondary back-up mooring. To possible satisfy the requirement of a two-line mooring line loss a solution with a second non-active mooring rope with a length that would allow the cage to surface can be installed.

For this initial design the feed platform is moored to the seabed with a 3-leg spread mooring system (each consisting of two mooring lines) where each line mockup consists of a wire section at top and a chain section at the seabed. The stud-link chain has a weight of 165 kg/m. In the future design of the fish farm 3 mooring lines will be used to ensure that the requirement for a 2-line missing ALS case is satisfied.

The cages are located approximately 250 meters from the center of the feed barge hence the Subfarm covers a circular area of approximately 0.2 km2 and as such can be located well within the mooring systems of each of the wind turbines.

5 Analysis and results

5.1 Analysis

As the purpose of these analysis is to provide input to noise assessment and to demonstrate that a wind turbine and a Subfarm fish farm indeed can share the same space the analysis and results will be given as general observations rather than detailed numerical data.

The analysis is carried out using the OrcaFlex which is an industry standard software for non-linear time domain simulations used in all marine industries. OrcaFlex has specific modules for modelling wind turbines which is used for the models herein.

We are running 1-hour (3600 seconds) simulations at 0, 45 and 180 degrees heading for the extreme combinations.

We have run the Subfarm in combination with the semi-sub wind turbine, to check for interference between the mooring systems for the two systems.

To derive input data to DHI we have carried out analysis for the two wind turbines separately to be able to deliver results within a reasonable analysis time.

Running a full system simulation with a complete fish farm and 4 wind turbines is extremely computational time consuming so we have run analysis with the wind turbines only and the fish farm only, but performed one simulation with a wind turbine and a fish farm for visual demonstration.

5.2 Results

From the dynamic simulations of all the different units we have extracted the main results, findings and the data to be used by DHI for their analysis.

5.2.1 Co-location space assessment

<u>Operational intact conditions</u>

Figure 5-1, below show the Subfarm and the semi-sub wind turbine from above in their static position with no wind, no current and no waves. The Figure 5-2 show the same situation for the extreme dynamic offset with max wind, current and waves.

It appears from the analysis that the global motion of the wind turbine and the global motion of the Subfarm including the motion of the mooring systems on the seabed demonstrates that the clearance is adequate. No clashing or conflict between the mooring systems of the two units is observed even if the Subfarm is moved more to the center between the two spread moorings from the wind turbine. The Table 5-1, confirms the limited motions of the three systems.

Hence, this show that the co-location from a hydrodynamic/motion point of view is acceptable.

Table 5-1: Mean and dynamic offsets for systems

Table of offsets		Subfarm		Wind Turbines	
		Feed Platform	Cages	Spar Buoy	Semi-sub
Mean Offset	**(m)**	10	1.5	8	13.2
Dynamic Offset	**(m)**	6	2.5	5.8	6.1
Maximum offset	(m)	16	4	13.8	19.3

Figure 5-1: Semi-sub wind turbine and Subfarm, static position

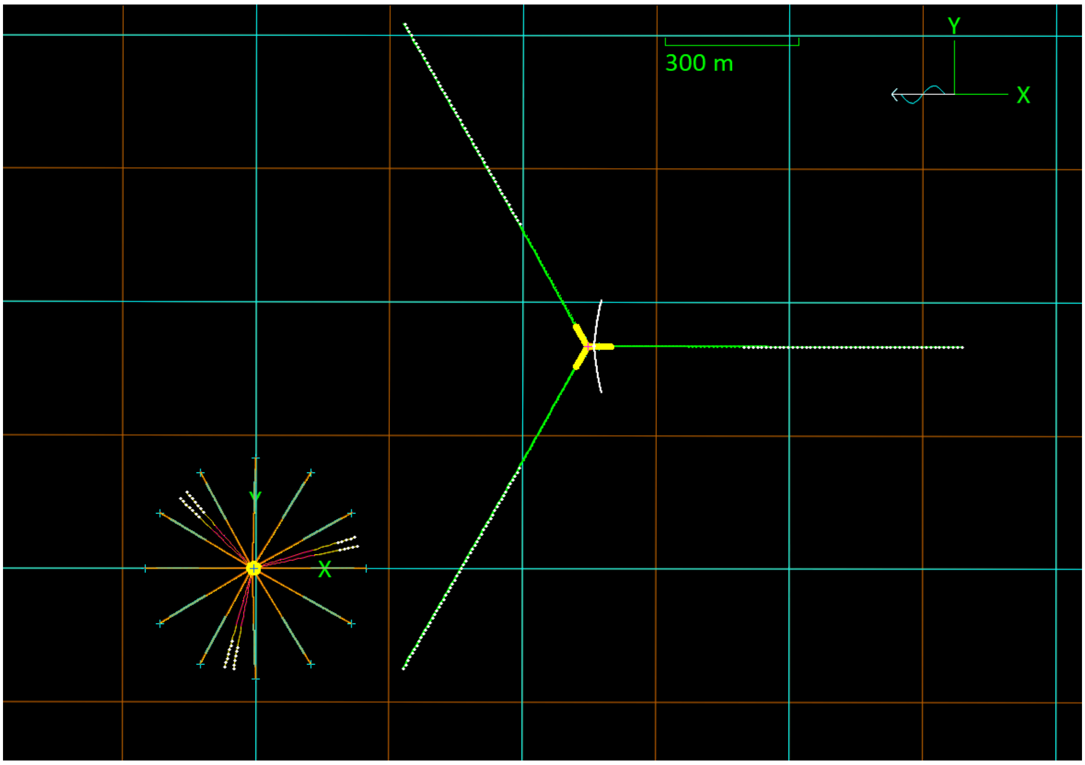
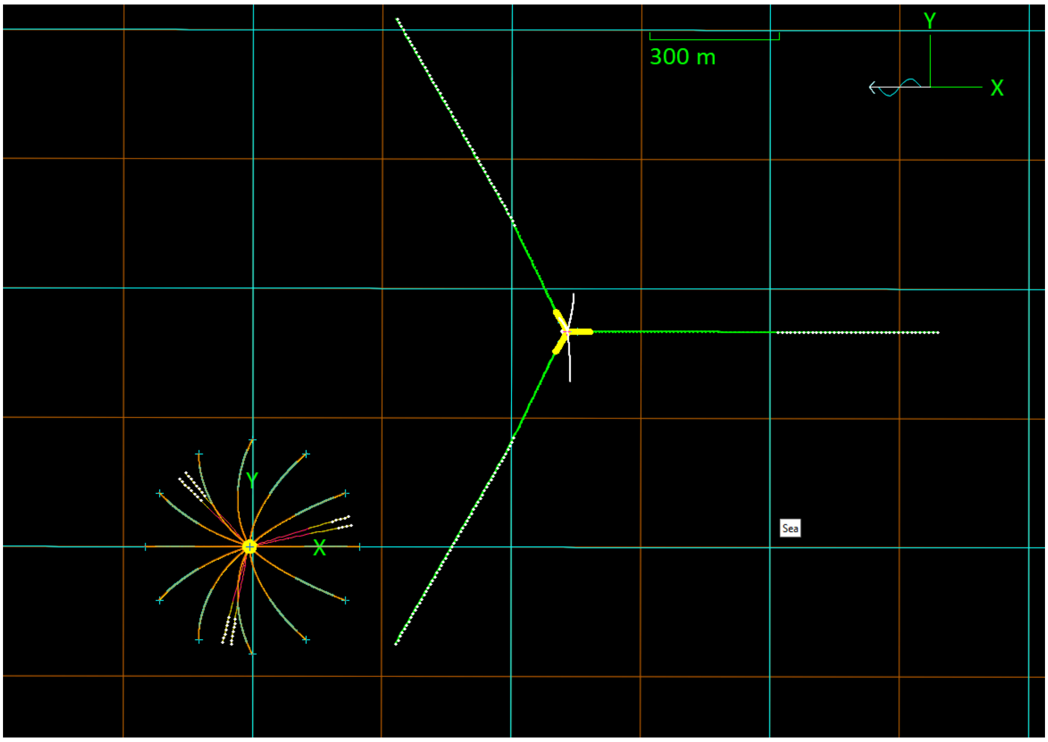


Figure 5-2: Semi-sub wind turbine and Subfarm, dynamic max positions



5.2.2 Wind turbine motions

The figures Figure 5-3 and Figure 5-4 show how the two wind turbines behave when exposed for wind, waves and current. The left part of the figures displays the un-loaded systems while the right part of the figures shows the wind turbines in their extreme dynamic load position.

As it can be observed the motions and offsets are relatively benign which also underpins the fact that co-existence with a Subfarm is feasible.

Figure 5-3: Spar wind turbine, static and dynamic

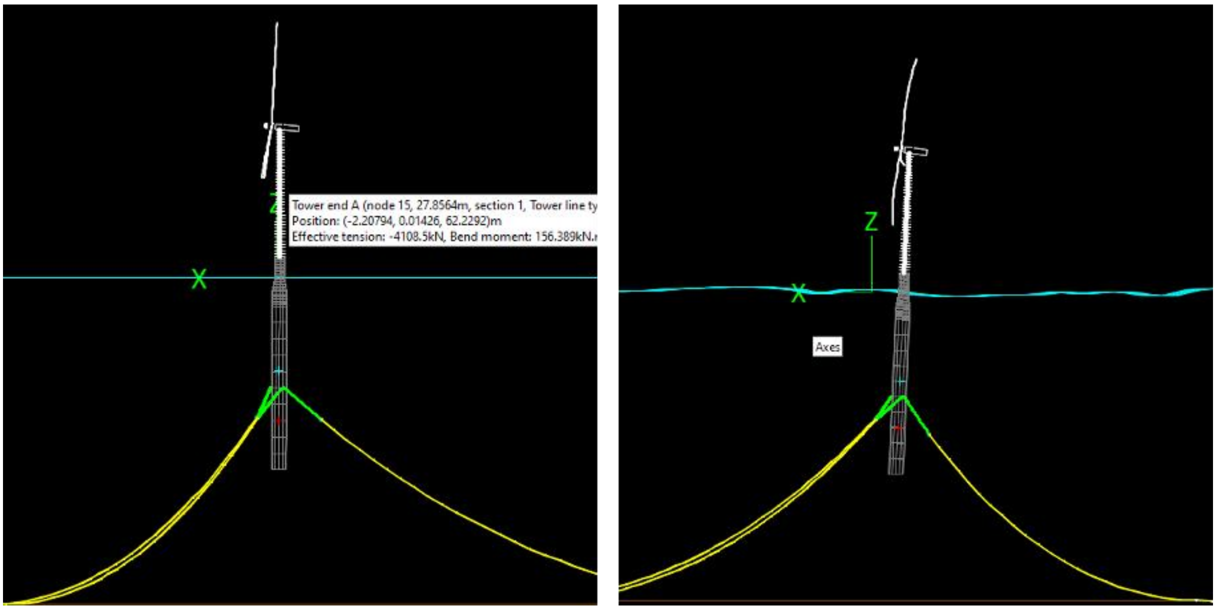
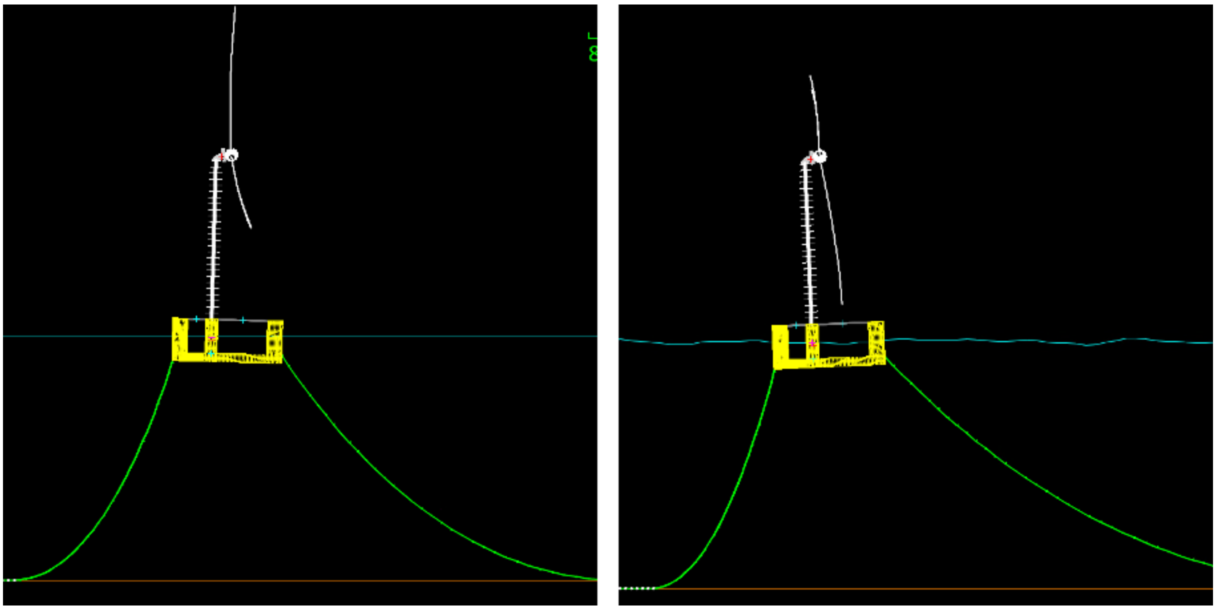


Figure 5-4: Semi-sub wind turbine, static and dynamic



5.2.3 Wind turbines performance, line tensions and offsets

We have run the simulations of the wind turbines using actual wind and power production. The purpose of these analysis is mainly to derive motions and loads in the mooring systems as well as offsets of the wind to provide data for noise calculations and checks on potential interference with the Subfarm system.

For completeness we have included the actual power produced by the wind turbine and the loads and tilts of the wind turbine.

Figure 5-5: Spar Buoy 5MW wind turbine power production

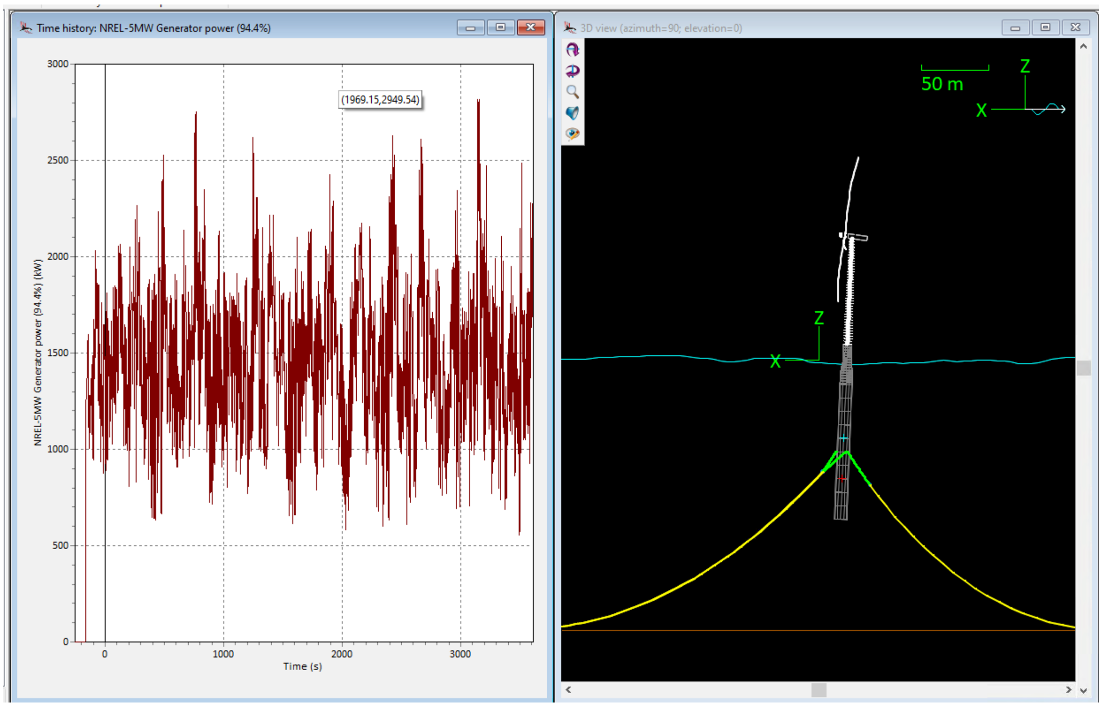


Figure 5-6: Semi 15 MW wind turbine power production

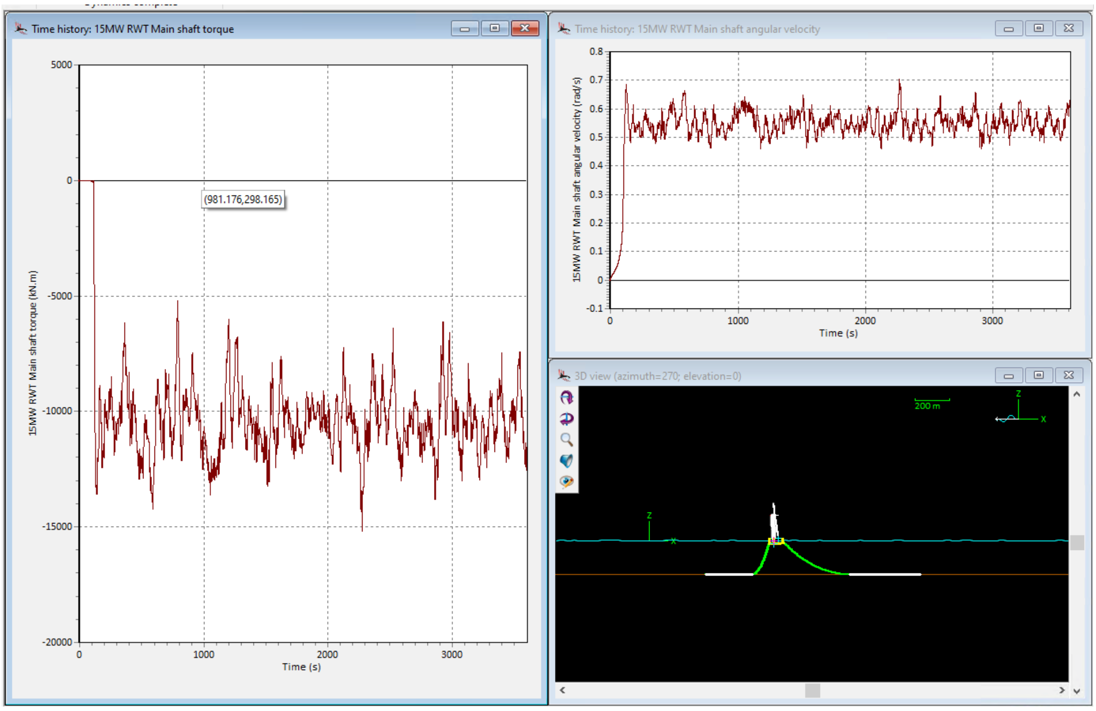
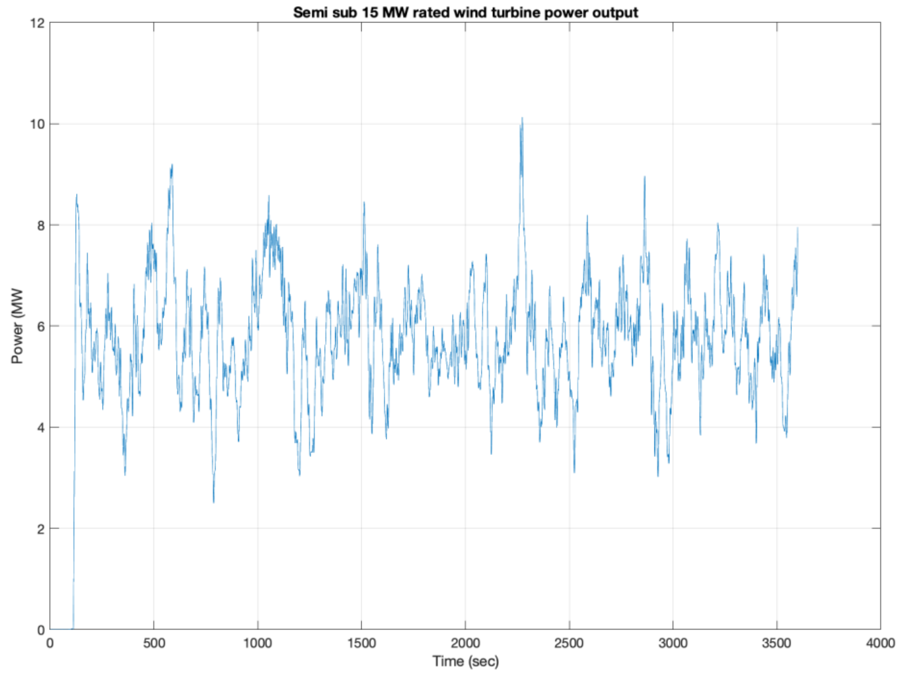


Figure 5-7: Torque and speed combined to Power for Semi Sub



The overall performance of the two units analyzed is shown in Table 5-2 below.

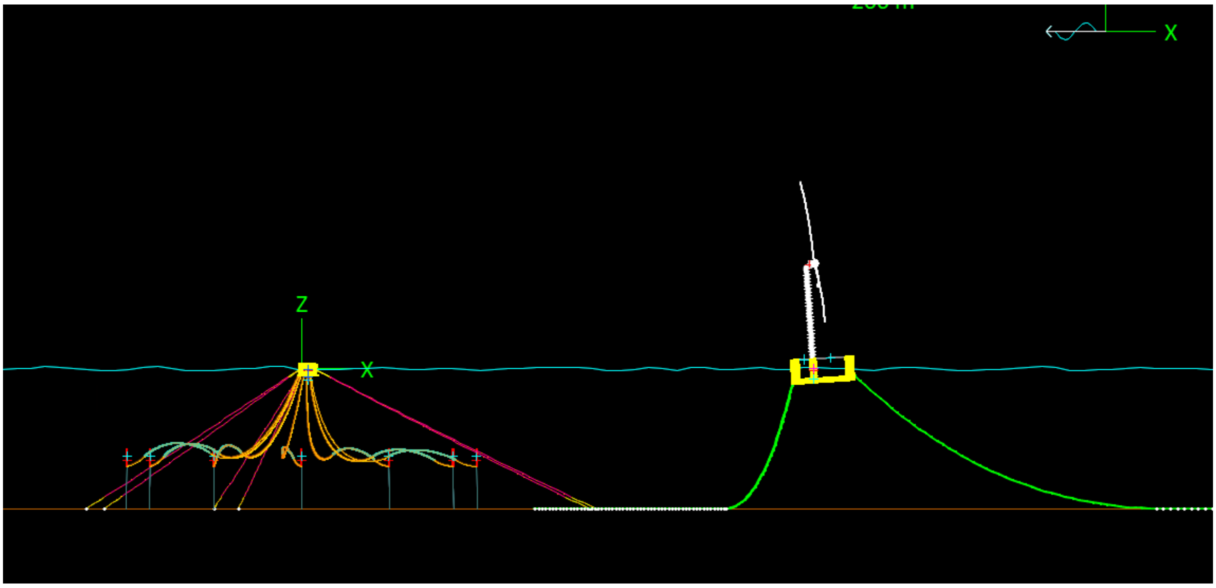
Table 5-2: Statistical Summary of Wind units performance and loads

Wind turbine Results NPD wind spectrum ref Mean Vind speed 7.3 m/s					
	(unit)	Min	Max	Mean	Std
Power production					
Spar Buoy (5MW rated)	(MW)	0	2.8	1.5	0.37
Semi Float (15MW rated)	(MW)	0	10.1	5.6	1.5
Motions					
Spar Buoy (5MW rated)	(deg tilt)	-6.7	-0.5	-3.0	0.9
Semi Float (15MW rated)	(deg tilt)	4.0	0.0	1.8	0.7
Load from Turbine to tower at top					
Spar Buoy (5MW rated)	(kN)	5662	6336	5948	74
Semi Float (15MW rated)	(kN)	22140	25912	24053	532
Mooring loads					
Spar Buoy (5MW rated)					
Line A	(kN)	253	432	319	26
Line B	(kN)	568	831	652	39
Line C	(kN)	307	438	353	18
Semi Float (15MW rated)					
Line A	(kN)	2171	3928	3388	217
Line B	(kN)	1858	2582	2092	80
Line C	(kN)	1856	2583	2095	80

5.2.4 Subfarm overall performance

The location of the Subfarm in this analysis is downwind for the 15 MW semi wind turbine. This is to check for potential co-location motion margines as it is seen in the early analysis that the wind turbines have larger offset than the Subfarm Figure 5-8.

Figure 5-8: Subfarm downwind of Semi-sub Wind Turbine



The analysis results for the Subfarm dynamic simulations are shown in the Table 5-3 below. The design is not optimized, but show reasonable offsets and motions. The data for offset and motions of the Subfarm is based on the results from the analysis of the Subfarm alone as seen in Figure 5-9 below.

Figure 5-9: Subfarm alone with slightly optimised mooring system

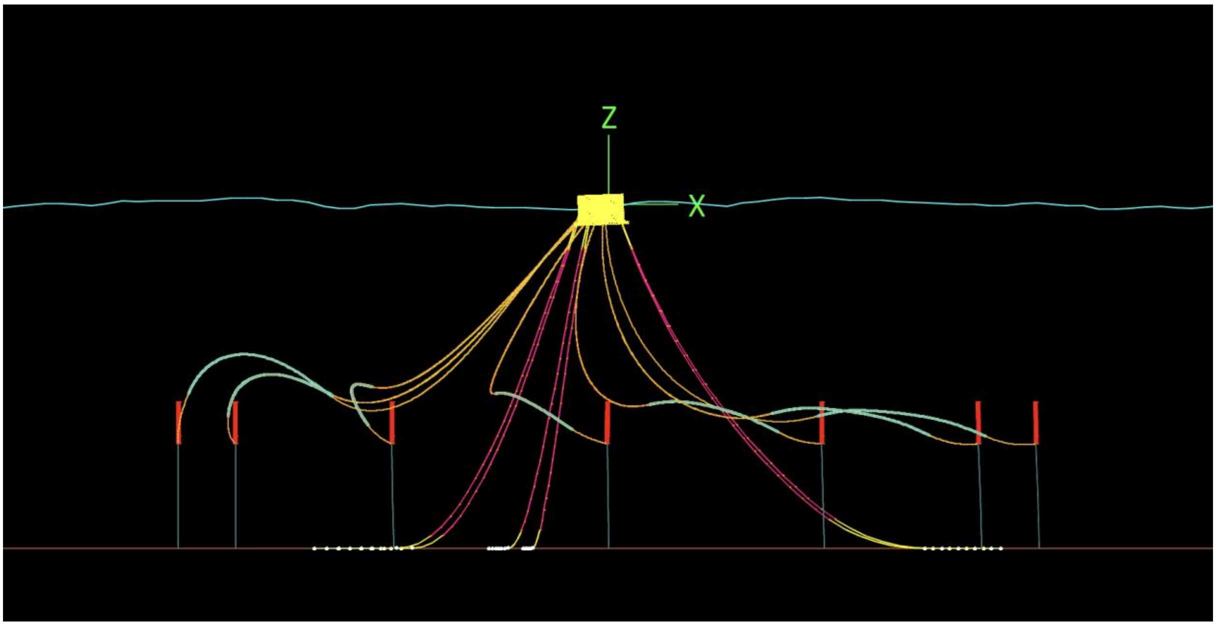


Table 5-3: Subfarm performance data

Subfarm Performance Statistics					
	(unit)	Min	Max	Mean	Std
Submerged Cages Offsets					
X	(m)	-4.00	0.50	-1.20	0.60
Y	(m)	0.00	0.00	0.00	0.00
Z	(m)	-0.30	0.01	-0.01	0.00
OffSet	(m)	0.69	0.11	0.26	0.03
Submerged Cages Winch Forces					
Cages	(kN)	106	132	107	2
Feed Barge Mooring Loads					
Line 1	(kN)	220	850	400	76
Line 2	(kN)	129	847	368	75
Line 3	(kN)	142	557	300	44
Line 4	(kN)	147	568	303	45
Line 5	(kN)	140	539	279	41
Line 6	(kN)	141	529	276	41
FeedBarge Offset					
X	(m)	4.1	16.1	9.9	1.5
Y	(m)	1.9	0.3	0.3	0.0
Z	(m)	-6.4	6.0	0.0	1.6
Total	(m)	4.5	16.1	9.9	1.5

Accidental Mooring Line Break

An important part of the design of a wind farm system or a Subfarm system will be the requirement to handle mooring line breaks in extreme conditions.

According to codes a system should be designed to withstand missing two mooring lines without this developing to a catastrophic event.

The design of the Subfarm has been carried out taking this into account. In the Subfarm it is mainly the Feed Barge that will be sensitive to a two mooring line break. Analysis has shown that if the single winch line for the cage breaks, the cage will surface and be pulled towards the feed barge and hence pose no risk for the wind farm. It has also been investigated if a non-active slack rope will be attached to the cage that will be activated if the winch wire breaks. This will effectively give a mooring system that can withstand the two mooring line break case.

The Feed Barge was initially designed with 3 groups of 2 mooring lines, but this has now been modified to be 3 groups with 3 mooring lines to be able to handle the two mooring line break case. The analysis with 2 mooring line broken show that the Feed Barg will still be well within the perimeter of the cages and hence pose no risk for the wind turbines.

Herein we have analyzed the case for the wind turbines where on corner upwind is missing to investigate how far the wind turbines will drift downwind in this case.

This is shown in Figure 5-10 and Figure 5-11 where the drift off after loss of one mooring line corner is shown. The 15 MW platform stabilizes at an offset of approximately 600 meter and the 5 MW spar stabilizes of an offset of 550 meters.

From theses simulations it is evident that the offset will be so large that it can drift into the Subfarm hence the total loss of a corner is not acceptable.

Figure 5-10: 15 MW semi offset after mooring line break

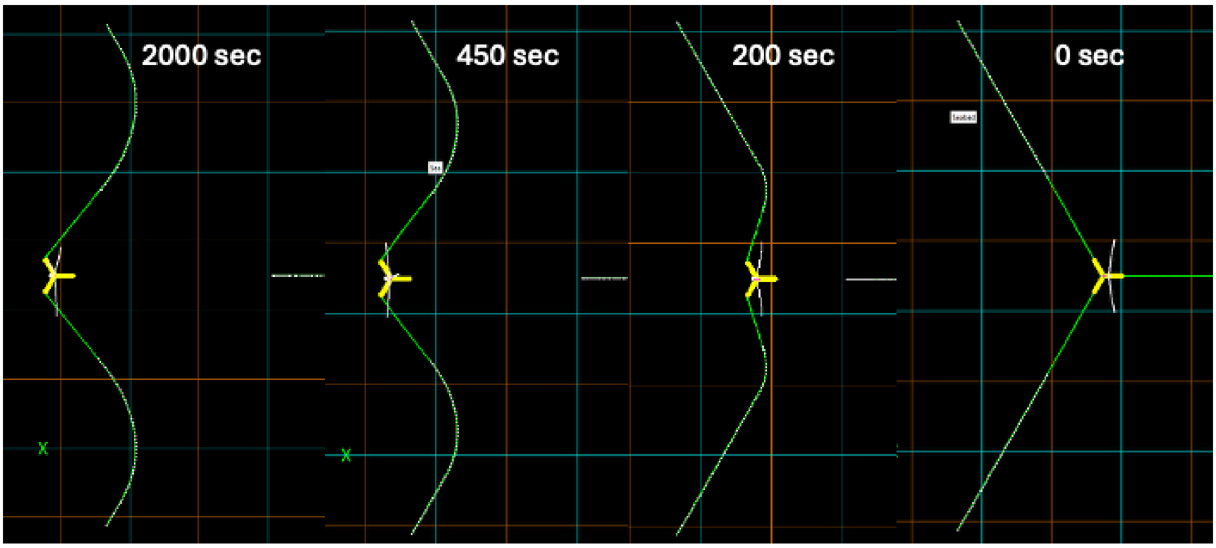
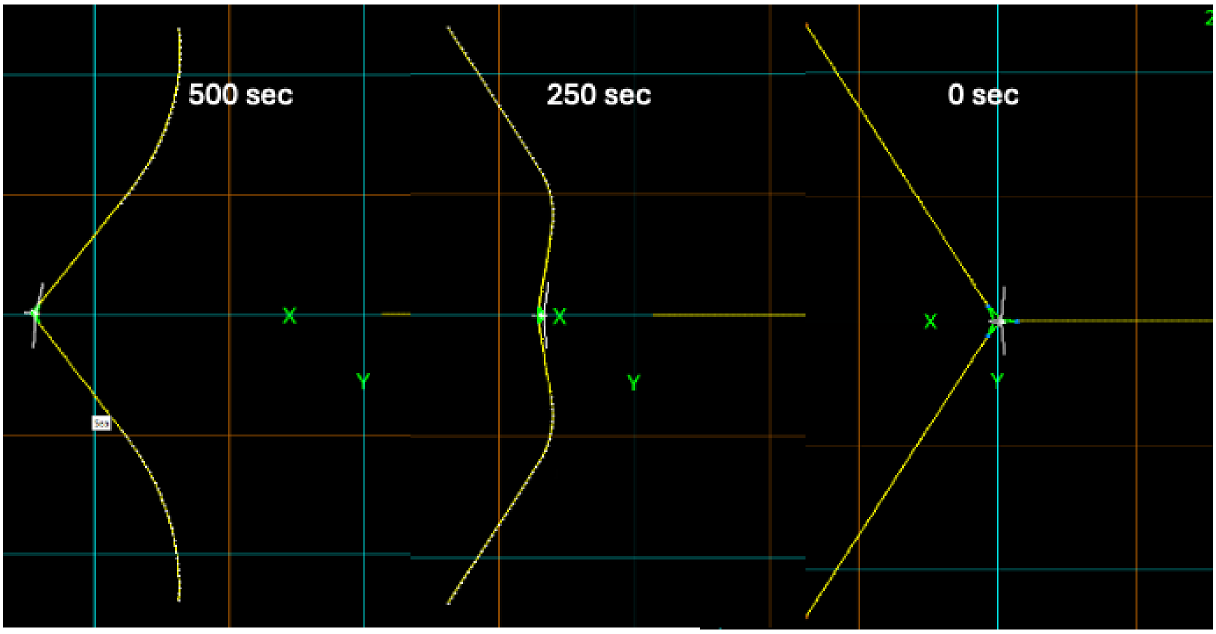


Figure 5-11: 5 MW Spar offset after mooring line break



To mitigate this effect and to ensure that the fish farm and the wind turbines can be co-located in the same marine space, the mooring group pointing away from the Subfarm will require as a minimum 3 mooring lines.

This will be the only modification that will be required on any of the systems to allow co-location of floating offshore wind and the Subfarm.

5.2.5 Data to DHI

DHI needs data for tension and accelerations of the different mooring systems as input to their noise modeling. The data is selected at the points were we see highest accelerations and motions on the lines.

Figure 5-12 and Figure 5-13 show the time series for the data required by DHI.

Figure 5-12: Tension and acceleration time series, Subfarm

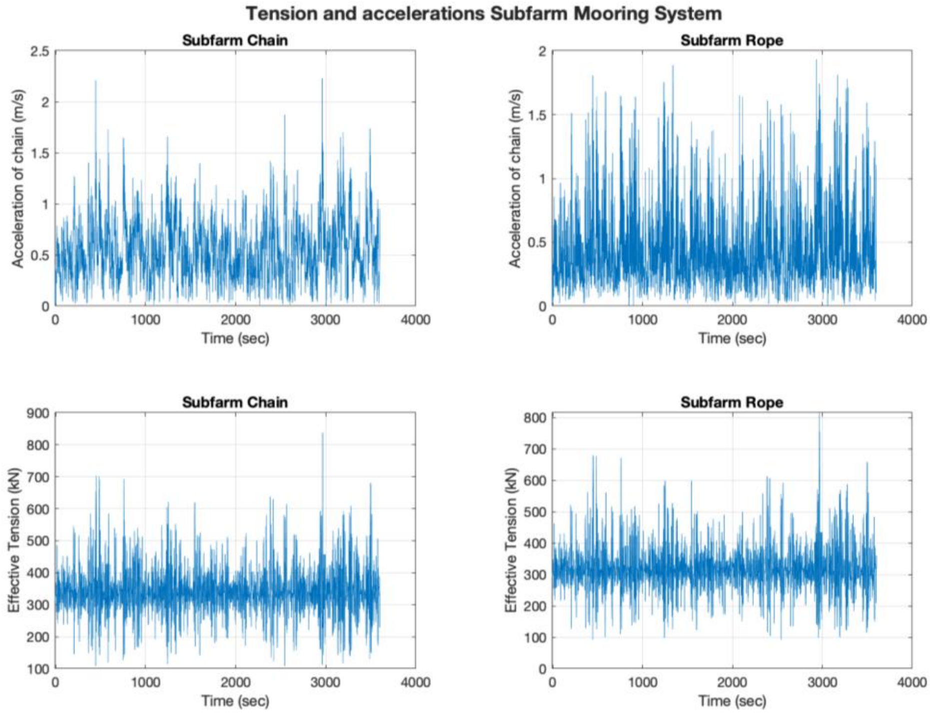
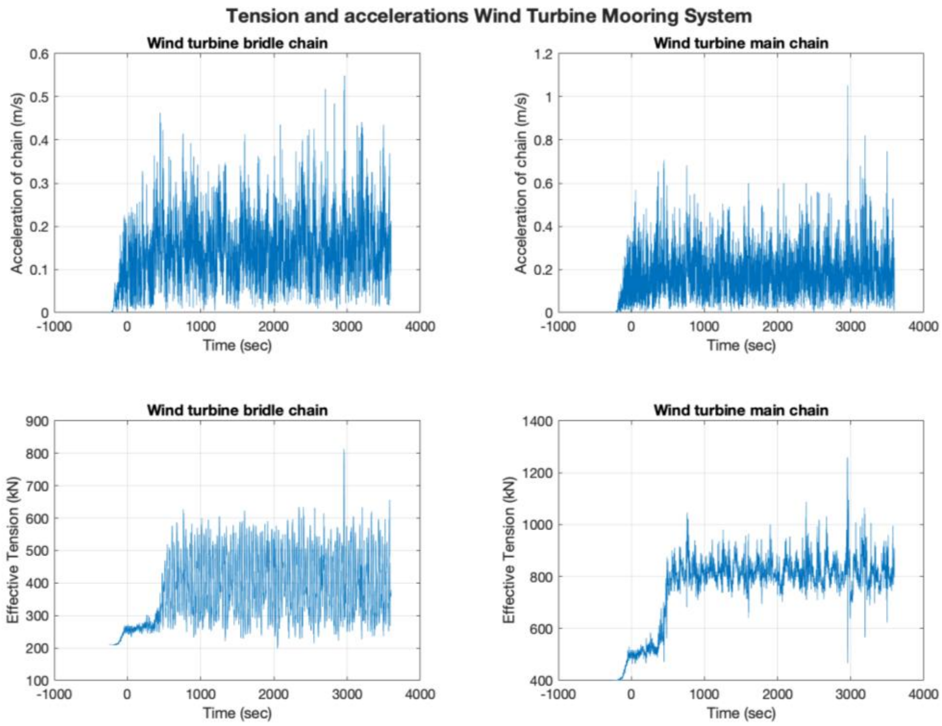


Figure 5-13: Tension and acceleration time series, Wind turbine



C. Underwater Noise Modelling and Impact Assessment Report

Offshore Floating Wind and Offshore Fish Farm (OFFWOFF) project

Project report WP3 - Underwater noise modelling and impact assessment input report

Report

14 May 2025

Prepared for Freja Offshore AB

The expert in **WATER ENVIRONMENTS**

Offshore Floating Wind and Offshore Fish Farm (OFFWOFF) project

Project report WP3 - Underwater noise modelling and impact assessment input report

Report

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Project No.:	11831064
Approved by:	Witold Skrzypinski
Approval date:	14 May 2025
Revision:	Final 1.0
Classification:	**Open**
File name:	11831064_Underwater_Noise_Final_Report_OFFWOFF.docx

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Nomenclature

Term	Definition
Effect	Changes caused by sound exposure that are an alteration from a prior state, condition, or situation, which is called the 'baseline' condition
Impact	Effects that reflect a change whose direction, magnitude, and/or duration might be sufficient to have consequences for the fitness of individuals or populations of individuals
Noise	Sound that is not a useful signal or cue, i.e., it has no adaptive value or biological meaning for the receiver, and may either be neutral or may have adverse effects
Sound	The acoustic energy radiated from a vibrating object, with no reference to its function or potential effect

Abbreviation	Definition
AUD INJ	Auditory injury that includes, but is not limited to, permanent threshold shift (PTS)
AQSV	Aquaculture Support Vessel
CTV	Crew Transfer Vessel
dB	Decibel – a logarithmic measure of sound intensity/pressure. Decibel value for acoustic pressure is 10 log10 (P^2/P_o^2) where P = actual pressure and P_o = reference pressure
HSD	Hydro Sound Damper system
Hz	Hertz – a unit of frequency, where 1 Hz = 1 cycle per second, 1 kHz is 1000 cycles per second
VHF	Very High Frequency
VHF-weighted SEL	Sound exposure level with the very high frequency weighting function in accordance with the susceptibility of hearing damage of porpoise caused by noise
NOAA	National Oceanic and Atmospheric Administration
OWF	Offshore Wind Farm
PTS	Permanent Threshold Shift due to a physical injury of hair cells as a result of exposure to noise
PW-weighted SEL	Sound exposure level with the frequency weighting function in accordance with the susceptibility of hearing damage of seals caused by noise
RAM	Range-dependent Acoustic Model
SEL	Sound Exposure Level: often used in marine environmental noise impact assessment and is the measure of the total sound energy normalised to 1 second
SEL_{cum}	Cumulative noise exposure level; summing up the noise exposure levels of many subsequent events. Calculated as:

Abbreviation	Definition
	$SEL_{cum} = SEL + 10 \log_{10} n$ n = number of pile driver strikes
SOV	Service Operation Vessel
SPL	Sound pressure level [dB re 1µPa] – sound pressure expressed in decibels [dB] relative to a reference pressure P_{ref}=1µPa
SPL_{peak}	Peak sound pressure level (signal amplitude maximum value)
SRC	Source
TL	Transmission Loss
TTS	Temporary Threshold Shift - a temporary threshold shift as a result of exposure to sound; the threshold will return to the pre-exposure state after some time
UAS	Underwater Acoustic Simulator
µPa	Micro pascal – a unit of pressure

1 Executive Summary

This report examines the generation, propagation, and potential impact of underwater noise on marine life due to the construction and operation of a combined floating wind- and fish farm. The study focuses on marine mammals, wild fishes, and farmed salmon and trout within the Mareld offshore wind farm area, which is shown in Figure . Conducted for Freja Offshore AB by DHI A/S (DHI) as part of the Offshore Floating Wind and Offshore Fish Farm (OFFWOFF) project, this analysis and report provides insights into the acoustic effects of the integration of aquaculture into a floating wind farm.

The environmental impact of underwater noise from offshore wind farms has been a key focus for regulators and scientists since the early 2000s. With the global expansion of offshore wind energy production, assessing and mitigating these impacts has become increasingly critical.

Freja Offshore AB is planning the Mareld Offshore Wind Farm (OWF) in the Skagerrak, approximately 40 km west of Lysekil, in the Swedish Economic Zone. The OFFWOFF project assessed synergies and possible environmental challenges of the co-location of floating wind turbines and submersible fish farming cages.

Within the OFFWOFF project consortium, DHI was responsible for the assessment of possible underwater noise impacts of the combined farms. Therefore, DHI conducted a comprehensive evaluation of the acoustical impacts associated with the construction, operation, and maintenance of the Mareld OWF and an offshore fish farm. This assessment aimed to determine the effects on marine mammals, wild fish, and farmed fish, particularly within nearby Natura 2000 protected areas. The key work packages included were:

1. **Underwater noise from wind farm installation**: Evaluating noise generated by different anchoring methods, including pile driving and suction anchor installation, with and without mitigation measures.
2. **Underwater noise from aquaculture installation**: Assessing the noise impact of suction anchors used for fish farm mooring.
3. **Operational and maintenance noise**: Modelling continuous noise from wind turbines, and fish farm operations, as well as discussing possible effects of noise caused by mooring lines and service vessels.
4. **Assessment of environmental impacts of noise levels on the different species**: Analysing cumulative noise effects on harbour porpoise, seals, wild fish and farmed salmon and trout using internationally accepted criteria and literature-based thresholds.

To fulfil the work packages, three key steps were required: source modelling, propagation modelling, and combining acoustic results with species-specific thresholds.

Source modelling defined the source levels and their distribution across the frequency spectrum. Propagation modelling determined how the noise spreads based on site-specific factors such as depth-dependent sound speed profiles and geo-acoustic soil characteristics. By combining these two models, the acoustic footprint of the offshore activities was obtained.

This acoustic footprint was then assessed against species-specific thresholds to evaluate the potential environmental impact of the underwater noise emissions.

The key findings of the modelling and the literature review on service vessel noise are:

- **Pile driving noise**: The highest impact ranges were observed for unmitigated pile driving. The consideration of noise mitigation measures significantly reduces these impact ranges as described below:
  - *Harbour porpoise*: Maximum behavioural impact range reduced from 63 km to 14 km, TTS impact range from 10 km to 100 m, and auditory injury range from 200 m to 100 m.
  - *Seals*: Behavioural impact reduced from 6.3 km to 400 m, TTS impact from 43 km to 3.7 km, and auditory injury from 5.9 km to 100 m.
  - *Fishes with a swim bladder*: TTS impact range decreased from 22 km to 1.3 km, and recoverable injury range from 900 m to 100 m.
  - *Fishes with the swim bladder involved in hearing*: Behavioural impact range decreased from 116 km to 19 km
  - *Farmed salmon and trout:* No behavioural threshold for pile driving noise could be identified during the conducted literature review for the farmed fish. The TTS impact is reduced from 17 km to 1.3 km, and recoverable injury range from 1.3 km to 100 m.
  - Overlapping impact areas with at least one of the Natura 2000 areas may occur also for mitigated pile driving, especially for the behavioural response of harbour porpoise and TTS of seals depending on the actual piling location.
- **Aquaculture farms** should not be located close to pile driving locations. With noise mitigation measures in place the maximum range of TTS for the farmed salmon and trout for this specific scenario is 1.3 km. However, stress responses, though not quantifiable, may occur at greater distances. For suction anchor installation and operational noise, TTS impact ranges are significantly shorter, remaining under 100 m. Therefore, maintaining a minimum distance of 100 m between floating wind turbines and fish cages is considered safe during operation.
- **Continuous noise sources (suction anchor installation, wind farm and fish farm operations, mooring lines, and vessel noise)**: These noise sources generally resulted in local impact areas centred around the turbine, vessel or the fish farm location, with behavioural, TTS, and injury impact ranges for harbour porpoises, seals, and farmed salmon and trout remaining to be comparably very small (**<**121 m).
- **Cumulative impact of wind farm and aquaculture:** The underwater noise added due to the fish farming activity is leading to a minor increase in the underwater acoustic footprint of the combined farms compared to the scenario with only wind turbines. The added impact areas are restricted to the fish farm location.
- **Farmed salmon and trout sensitivity to noise:** While farmed salmon and trout are less sensitive to underwater noise, stress and behavioural responses may occur at lower thresholds than TTS. However, a dedicated threshold for a stress response and a behavioural response threshold for pile driving noise remains uncertain due to limited scientific data.
- **Data gaps:** During the review of the available literature, several data gaps and research needs were identified. These included a lack of species-specific criteria, limited consideration of fish mobility in existing criteria, methodological issues in some studies preventing their use for reliable thresholds, and an overall insufficient number of species-specific studies to establish certain criteria. In most cases, these gaps were addressed through well-considered assumptions. Recommendations have been provided to help fill these gaps and support the development of more robust and informed future assessments.
- **Service vessel noise:** A qualitative assessment of operational noise from offshore wind farm and aquaculture maintenance vessels indicated potential for localised influence on marine fauna.

However, given the intensity of the service vessel traffic and typically short ranges of influence, the associated noise is not expected to result in substantial effects on the marine fauna. Given the limited number of studies, particularly on fish, and rising global underwater noise levels, precautionary measures such as reduced vessel speed are recommended to mitigate potential cumulative impacts.

The study confirms that noise mitigation strategies, such as a Hydro Sound Damper system, significantly reduce the impact of pile driving on the marine life, even in deep water. The considered continuous noise sources result in small local impact areas for the different kinds of hearing impairments and behavioural response of harbour porpoises. Furthermore, only localised influences of the service vessel noise are expected. Overall, the fish farm does not significantly add to the underwater noise or environmental impact associated with the construction and operation of the Mareld OWF.

2 Introduction

This report prepared for Freja Offshore AB provides the results of the underwater noise assessments conducted by DHI A/S (DHI) within the framework of the Offshore Floating Wind and Offshore Fish Farm (OFFWOFF) project, which is co-sponsored by Nordic Innovation.

2.1 Project Background

The effects of underwater noise from offshore wind farms on marine life have been in the focus of regulators and scientists since the turn of the century, when the first windfarm projects were planned off the coast of Denmark, see an early review by Thomsen *et al.* (2006). In recent years, and in conjunction with the plans to accelerate the development of offshore wind on a worldwide scale, the issue has become even more important with some major reviews based on the newest knowledge (see, for example, Thomsen *et al.* (2016)). The emission of underwater anthropogenic sound can adversely impact aquatic animals (Duarte *et al.* 2021; Thomsen *et al.* 2021). Consequently, noise modelling is required to verify whether the emitted sound levels during construction and operation will negatively impact the marine fauna and to identify the potential need for mitigation measures.

Freja Offshore is planning to build and operate the Mareld Offshore Wind Farm (OWF) in the Skagerrak, approximately 40 km west of Lysekil, in the Swedish Economic Zone with a minimal distance to shore of approximately 37 km as shown within Figure . There is a Danish Natura 2000 area 600 meters south of Mareld: Skagens Gren and Skagerrak (DK00FX112), which is an important breeding and resting area for porpoises. Furthermore, the Swedish Bratten Natura 2000 area is located in the north of the planned OWF. The Bratten Natura 2000 site encompasses valuable habitats such as reefs, which support various marine organisms, including fish (Natura 2000 Viewer 2025). The area is known for the presence of numerous fish species, such as Atlantic cod, cusk, herring, flounders, rays and sharks (Danish Fisheries Agency 2025). Both Bratten and Skagens Gren and Skagerrak are also designated Marine Protected Areas (MPAs) (OSPAR 2018).

The windfarm is planned to consist of floating wind turbines moored to the seabed by anchors. In parallel, Subfarm AS is advancing offshore aquaculture with submersible fish farming cages designed for the harsh marine environment. Within the framework of the OFFWOFF project (Nordic Innovation 2024), the synergies and challenges of co-locating a wind farm and offshore fish farms are being investigated. One key aspect of the OFFWOFF project is the assessment of the influence of underwater noise generated during the installation, operation, and maintenance of the wind and fish farms on the marine fauna, such as harbour porpoise seals and wild fish, as well as the farmed fish species salmon and trout. The assessment should consider these species in general and specifically within the protected Natura 2000 areas, to determine whether mitigation measures are necessary to ensure compliance with environmental regulations.

Within the OFFWOFF consortium, DHI was responsible for evaluating the biological impact of underwater noise associated with the combined activities of floating offshore wind and offshore fish farming. The findings are supposed to help inform sustainable development practices and minimize potential ecological disturbances.

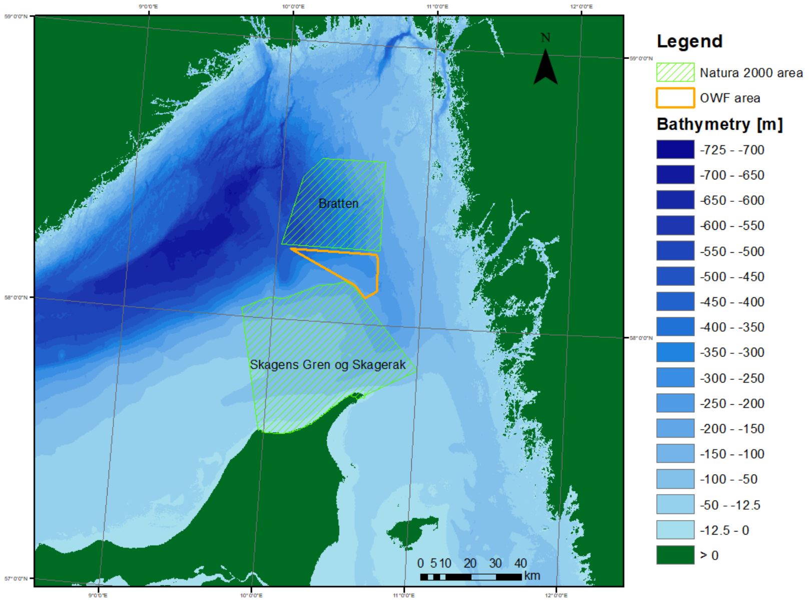

Figure 2.1 **Map of the Mareld OWF area (yellow polygon) and adjacent Natura 2000 areas (green polygons) in the Skagerrak**

2.2 Key project parameters

An overall goal of the OFFWOFF project is that the outcome of the investigations is also applicable to similar projects in other locations. In order to compare the outcome from the investigations to the impacts in another location, the project parameters should be similar. However, a conclusive definition of when two projects are actually similar is difficult. When comparing the parameters, it needs to be distinguished between parameters that influence the propagation of underwater noise, parameters that define the source strength and parameters that influence the total acoustical dose.

Parameters that influence the propagation are, e.g., the water depth, the sound speed profile, and the soil characteristics. The water depth is ranging from 191 m to 452 m within the Mareld OWF. The sound speed profile was derived for the summer season and is showing a thermocline for the first 100 m, where it decreases from 1500 m/s to 1483 m/s, as shown in Figure A-10. The considered soil profile consists of low strength to high strength silty clay for the first 15 m and medium to very high strength clay with sand for another 17 m. The respective profile is displayed in Figure A-11.

The important parameters for the description of the source strength of the pile driving noise for deep water scenarios are the pile diameter (2.5 m), the maximum strike energy (800 kJ), the length of the pile (45 m), and the considered hammer type (Menck MHU 800S with a ram weight of 80 t).

Relevant parameters for the total acoustical dose are the cumulation time for continuous noise, which was set to 24 h. In the case of pile driving, the penetration per strike in combination with the strike energy schedule are driving the total acoustical dose. The considered total number of strikes was 7700.

The operational noise from the combined wind and fish warm is depending on the number of turbines and aquaculture. A layout with 136 turbines with a nominal power of 15 MW per turbine is considered for the wind farm and three locations of the aquaculture. The individual turbine and fish farm locations are displayed in Figure 2.2.

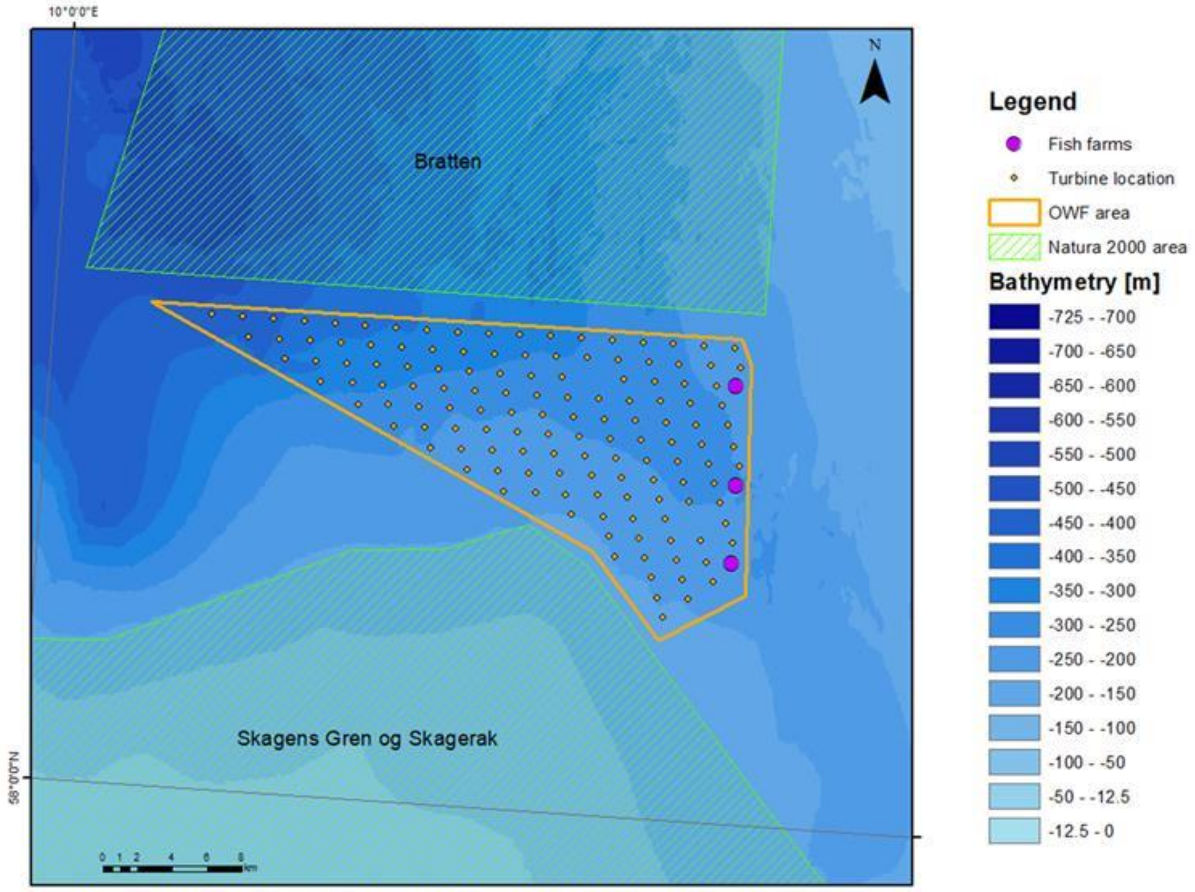

Figure 2.2 Map of the turbine and fish farm locations of the Mareld OWF area

2.3 Scope

Within the OFFWOFF consortium, DHI is responsible for executing the following four work packages. Their definition is repeated below, along with a short description of how DHI approached and implemented them.

1. **Underwater noise from the windfarm installation**:
   Assessment of underwater noise generated by activities linked to the construction of the offshore wind farm. Models will be developed to estimate the noise levels at the source as well as their propagation in the surrounding areas. Common mitigation strategies will also be considered and assessed.

   DHI approach and implementation:
   There are many different options for the installation of anchors for the floating wind turbines. The acoustical worst-case is impulsive pile driving. Therefore, a realistic pile driving scenario was defined in Section 3.2.2. The impacts were evaluated for an unmitigated and a mitigated scenario in Section 4.1.

   Furthermore, the underwater noise from a suction anchor installation was considered for the installation of the aquaculture, which could be an alternative anchoring technology for the floating turbines.

2. **Underwater noise from the aquaculture installation:**
   Assessment of underwater noise generated by activities linked to the installation of the offshore fish farm. Noise levels will be estimated using source and noise propagation models.

DHI approach and implementation:
The preferred installation technique for the fixation of the aquaculture farm is a suction anchor. This method could also be used for the anchorage of the floating wind turbines. The approach for the evaluation of the pumping and vessel noise caused by the suction anchor installation is described in Section 3.2.3 and the impacts that could result from these aquaculture installation activities are described in Section 4.2.

3. **Underwater noise from the operations and maintenance:**
Estimation of underwater noise levels generated during operations and maintenance of the combined offshore farms.

DHI approach and implementation:
The operational and maintenance noise of the combined farms is assessed as follows. The operational noise of all floating turbines was modelled numerically. The modelling approach for the operational noise is outlined in Section 3.2.4 and the resulting impacts are shown in 4.3.1 The underwater noise caused by the operation of the aquaculture is combined with the underwater noise emitted by the operating turbines and their cumulative impact is assessed.

Furthermore, the effects of the underwater noise caused by mooring lines and supply vessels are discussed.

4. **Assessment of environmental impacts of noise levels**:
Noise levels estimated during previous tasks will be combined and assessed in the light of their impacts on marine species in the surrounding areas as well as fish species being farmed. The outcome will provide a comprehensive environmental assessment of the cumulative underwater noise impact of combining offshore wind and fish farms.

DHI approach and implementation:
The impacts on harbour porpoises, seals, and fishes caused by the underwater noise emitted in the different scenarios are evaluated by combining internationally accepted criteria and state of the art research results with the modelled underwater noise levels. Furthermore, a literature study was conducted to identify thresholds for the farmed fish species.

3 Methodology

The methodology described in this section provides the framework for assessing underwater noise impacts. The approach is divided into four key components: overview of the general approach, source modelling, propagation modelling, and the calculation of biological impacts. This approach covers the characteristics of noise emissions from various sources, simulates the propagation of sound through the marine environment and calculates the potential biological effects of the emitted underwater noise on marine life.

3.1 General approach

DHIs approach to the estimation of impact ranges and areas comprises three steps:

- Sound source definition (sound level and frequency spectrum)
- Numerical propagation modelling
- Calculation of biological effects using internationally accepted criteria

The used **sound source definitions** for the different kinds of sources were all based on measurement data, which was scaled (if necessary) to fit to the actual project parameters. Further details are provided in the description of the individual sources within Appendix A.1.

The **numerical propagation modelling** was performed using a parabolic equation model incorporated in the in-house MIKE by DHI Underwater Acoustic Simulator (UAS) (DHI 2023). The model focuses on noise propagation in the far field. UAS uses the RAM code based on the sound propagation model developed by Collins (1993). A detailed description of the underwater acoustic model, including the scientific basis and the assumptions of the model, is included in the technical documentation for UAS in MIKE (DHI 2023).

The sound source models were combined with the propagation models to calculate the sound propagation in angular directions from the source location at 72 transects in 2D. Specific 1/3 octave bands with centre frequencies from 20 Hz to 4 kHz were modelled. For higher frequencies, the propagation losses at 4 kHz were applied in combination with a correction for the increasing volume attenuation with increasing frequency (Francois and Garrison 1982a, b). Based on the numerical model, maps were derived presenting the sound levels as a function of bearing angle and distance from the sound source. Since the marine mammals and fish covered in this study use the entire water column, the maximum sound levels in the water column were used as a basis for the calculation of impact ranges, if not stated differently.

The **calculation of biological effects** was performed using the framework presented by Thomsen *et al.* (2021). Accordingly, there are several overlapping zones of noise effects which dimensions mainly depend on the relative distance of the animal to the location of the sound source (Figure). In this study, the focus is on the **behavioural response** and the **hearing impairment** - Temporary Threshold Shift (TTS), Auditory Injury (AUD INJ) and recoverable injury in the case of fish, since these are the effects that need to be considered due to existing regulations.

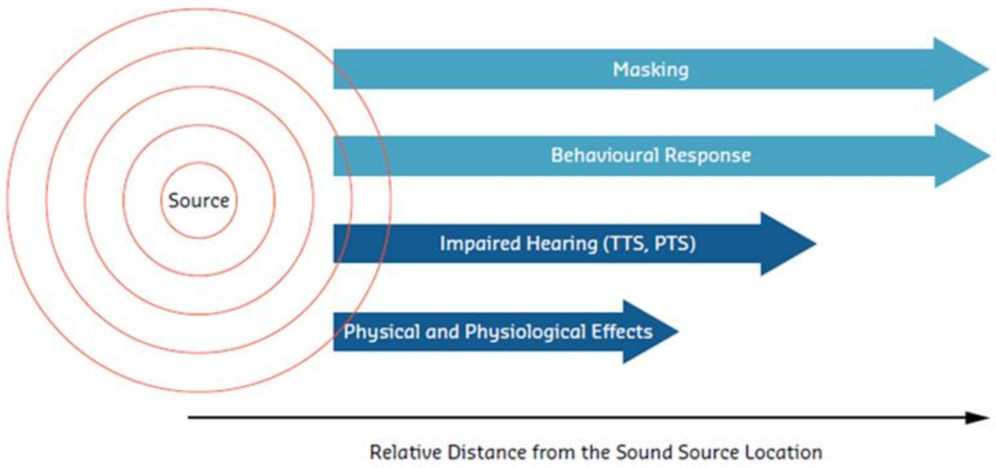

Figure 3.1 Potential effects of noise at different distances from a sound source (taken from Thomsen *et al*. (2021))

With PTS standing for permanent threshold shift, nowadays referred to as auditory injury.

3.2 Underwater noise modelling

The underwater noise modelling approach consists of two sub-models. These include the source model and the propagation model.

3.2.1 Propagation modelling

DHI selected the location of the sound source to be representative for the entire wind farm with an intermediate water depth, given that a single position had to be chosen. The considered source location is shown in Figure and the coordinates are provided in Table 3.1. The bathymetry was obtained from the high-resolution bathymetry dataset from the European Marine Observation and Data Network (EMODnet). Two different source depths were evaluated. These are 215 m below the sea surface, which was considered for the pile driving activities and the pump for the suction anchor installation as well as 30 m below the sea surface for the operational noise of the turbines and vessel noise of the construction vessel.

Table 3.1 Sound source location

Longitude	Latitude	Source depths
58º 07’ 48” E	10º 39’ 14” N	215 m / 30 m

Based on previous studies and literature data (Thomsen *et al*. 2006), it was determined that the area subjected to modelling should comprise a radius of a maximum of 150 km from the source of sound in all directions. Therefore, 72 transects of 150 km or less were determined, depending on the coastline barrier as shown in Figure .

From an acoustic point of view, the area is considered as deep water. The propagation characteristics are dominated by the depth-dependent sound speed and attenuation profiles as well as the geo-acoustic properties of the sea floor. These are provided in Appendix A.2.2 and Appendix A.2.3.

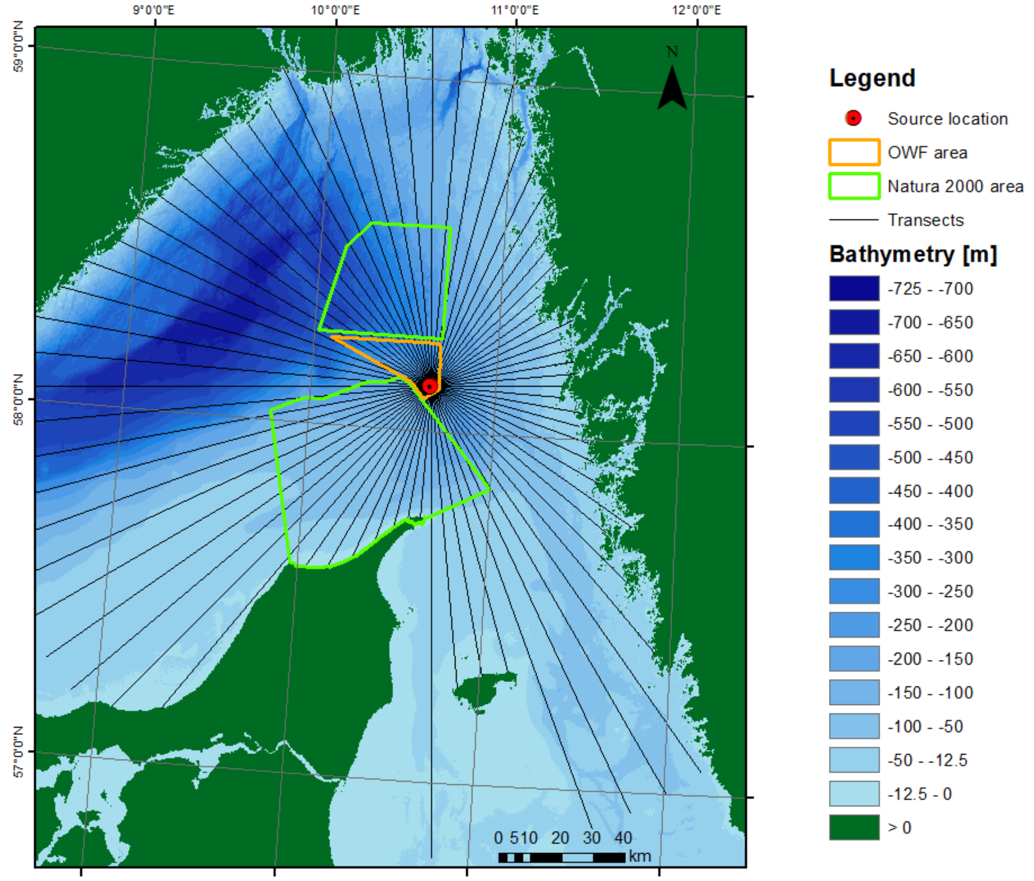

Figure 3.2 Map of directions of sound propagation modelling at the Mareld OWF location

3.2.2 Source modelling - pile driving

Pile driving was already assessed in a study by DHI prior to the OFFWOFF project (Kaji *et al.* 2023). Underwater pile driving noise modelling is a field of continuous scientific developments. Therefore, the underwater noise modelling approach for pile driving has been slightly refined in the meantime to produce more realistic acoustic results and, consequently, more accurate impact ranges.

The main differences are:

- Reduction of noise levels with decreasing wetted surface as shown by Lippert *et al.* (2017)
- Including the typical ramp-up of the strike energy at the beginning of pile driving
- Including driveability results within cumulative noise level impacts (less strikes per penetration at the beginning of piling and more strikes at the end)
- Measurements are scaled to account for the MHU 800S hammer ram weight

The decreasing radiating surface with increasing penetration depth was considered by including the trend in the sound levels described by Lippert *et al*. (2017). They show a decrease in the sound levels with decreasing wetted surface. This influence was combined with the blow count provided by Freja (see Figure A-2) and a ramp-up strike energy profile (provided in Table A-3). The total number of blows was 7770. The combination of all three influences leads to a more realistic but still conservative estimate of the sound levels and consequently more accurate impact ranges.

The used parameters, the applied strike energy profile, the considered penetration per strike and the resulting source levels are provided in Appendix A.1.1.

3.2.3 Source modelling - suction anchor installation

The noise from suction anchor installation is primarily caused by the construction vessel, as shown in measurements from Borkum Riffgrund 1 (Remmers and Bellmann 2015). The pump noise dominates only at frequencies above 1 kHz. Measurements were scaled to a virtual point source. A key difference between the shallow measurement site and the deep water at Mareld OWF is the separation of noise sources: in shallow water, vessel and pump noise originate from similar positions, whereas in deep water, they come from distinct locations (pump near the seafloor, vessel near the sea surface). Therefore, the measurements were split into two source spectra. Further details are provided in Appendix A.1.2.

The noise from suction anchor installation is considered primarily for installing the fish farm, although this could also be an anchoring method for floating offshore wind turbines.

3.2.4 Source modelling - operational noise of the turbines

Operational noise was already assessed in a study by DHI prior to the OFFWOFF project (Kaji *et al.* 2023; Tarnoki and von Pein 2023). In the meantime, the general approach of the underwater noise modelling from operational noise has been adapted in order to account for the latest research.

The main differences are:

- No dependence of the source level on the nominal power of the turbine is assumed. Hence measurement data from a 6 MW turbine is assumed to be similar to the noise emissions of the considered 15 MW turbines.
- The total acoustic emission depends on the number of turbines instead of the nominal power. Therefore, the layout of the wind farm with 15 MW turbines is considered
- The highest available measured source level of a floating wind farm is considered as a conservative estimate of the source level (Hywind Scotland Floating Offshore Wind Farm)
- The application of the thresholds is updated

Early studies (Stöber and Thomsen 2021; Tougaard *et al.* 2020) suggested a positive correlation between wind turbine nominal power and operational noise. However, a more comprehensive study Bellmann *et al.* (2023) found no such relationship, showing that sound levels were independent of nominal power, drivetrain type, or foundation type. These findings were based on fixed-bottom turbines only. It was therefore determined to choose a measured spectrum that could be deemed most representative and conservative for the investigated case. More details and the applied source levels are provided in Appendix A.

3.2.5 Source modelling - operational noise of the aquaculture

Offshore aquaculture farms generate various potential noise sources, including vessel movements for feeding, harvesting, and treatments. Despite the vessel noise, feeding systems, and pumps are possible contributors to the soundscape.

In general, there are only a few noise measurements for the operational noise of offshore aquaculture available, and their focus is generally on the broadband levels. A recent review of the underwater noise at several Norwegian salmon aquacultures (Barrett and Oppedal 2025) was considered for the derivation of the source levels, which are provided in Appendix A.1.4.

3.3 Calculation of biological impact

Since the prior noise studies conducted by DHI (Kaji *et al.* 2023; Tarnoki and von Pein 2023), the definition of the NMFS criteria has changed (NMFS 2024). Furthermore, the updated behavioural threshold defined by (Tougaard 2021) for the harbour porpoise was applied. For fish, the PTS criterion has been replaced by recoverable injury, according to the expertise knowledge on impacts of noise on fish hearing (Popper and Hawkins 2019; Popper *et al.* 2014)

The main differences applied in the calculation of the biological impacts are:

- Change in naming convention of the hearing groups. The harbour porpoise is grouped within the very high frequency (VHF) hearing group
- Change in the definition of the weighting curves for seals and harbour porpoises (NMFS 2024)
- Changes in the definition of the thresholds for seals and harbour porpoises (NMFS 2024)
- For marine mammals, the term permanent threshold shift (PTS) is replaced by auditory injury (AUD INJ)
- For fish with a swim bladder, the term permanent threshold shift (PTS) is replaced by recoverable injury (Popper and Hawkins 2019; Popper *et al.* 2014).
- The behavioural threshold for pile driving noise affecting harbour porpoise has been updated with the frequency weighted threshold defined by Tougaard (2021)

The impacts were determined using noise criteria which describe received noise levels that should not be exceeded in order not to cause harm to marine life. The existing criteria have been developed mainly for the hearing impairment, i.e., TTS and auditory injury in marine mammals, as well as the recoverable injury for fishes (NMFS 2024; Popper *et al.* 2014).

Although behavioural response criteria are less established due to their complexity and individual variability, there are noise level thresholds defined for inducing behavioural reaction of the harbour porpoise and seals (Tougaard 2021, Russel et al. 2016). In case of fish with the swim bladder involved in hearing, a threshold for the behavioural reaction was applied based on the study of Hawkins *et al*. (2014).

The cumulation within the assessment of the impact of pile driving noise was conducted for one pile installation per day.

3.3.1 Threshold values used for pile driving noise

Harbour porpoise and seals

For marine mammals, the hearing impairment criteria, i.e., TTS, AUD INJ resulting from impulsive noise are based on NMFS (2024). The cumulative SEL considers all strikes that are necessary for the installation of one pile.

The threshold for the behavioural response of harbour porpoises was taken from Tougaard (2021). It is defined as the VHF-weighted SPL_{125ms}. In this case, the VHF weighting refers to the definitions of Southall *et al.* (2019).

The behavioural reaction threshold for seals is based on the research of Russell *et al.* (2016).

A summary of the threshold values is presented in Table 3.2.

Table 3.2 Overview of the noise exposure criteria for marine mammals used for the calculation of impact ranges for pile driving noise

Source	Effect	Marine Mammal species	Single strike / cumulative	Sound level type	Threshold	Unit
NMFS 2024	AUD INJ	Harbour porpoise	cumulative	VHF-weighted SEL	159	dB re $1\mu Pa^2s$
			Single strike	SPL_{peak}	202	dB re $1\mu Pa$
	TTS	Harbour porpoise	cumulative	VHF-weighted SEL	144	dB re $1\mu Pa^2s$
			Single strike	SPL_{peak}	196	dB re $1\mu Pa$
NMFS 2024	AUD INJ	Harbour and grey seal	cumulative	PW-weighted SEL	183	dB re $1\mu Pa^2s$
			Single strike	SPL_{peak}	223	dB re $1\mu Pa$
	TTS	Harbour and grey seal	cumulative	PW-weighted SEL	168	dB re $1\mu Pa^2s$
			Single strike	SPL_{peak}	217	dB re $1\mu Pa$
Tougaard 2021	Behavioural reaction	Harbour porpoise	Single strike	VHF-weighted SPL_{125ms}	103	dB re $1\mu Pa$
Russel *et al.* 2016	Behavioural reaction	Harbour and grey seal	Single strike	unweighted SEL	158	dB re $1\mu Pa^2s$

Animal movement model for marine mammals

According to the Skjellerup guideline (Skjellerup *et al.* 2015), marine mammals tend to escape radially from the pile driving location with a given escape speed (v =1.5 m s^{-1}). The received noise dose is then cumulated along the way of the escaping mammal, and due to the increasing distance from the source, it is smaller than for the static individual staying in one location while impacts accumulate. Moreover, the Skjellerup guideline further assumes an initial radius r_0 that is free of mammals. This radius should be chosen in such a way that mammals can escape without experiencing a hearing injury. In the conducted modelling, the behavioural thresholds for marine mammals in response to pile driving are included in the animal movement / fleeing model in the way that the animal stops fleeing once it crosses the behavioural impact range.

Fishes with a swim bladder

Fishes with a swim bladder can be grouped into two hearing categories – species with the swim bladder involved in hearing and species with a swim bladder not involved in hearing. The first group is characterised by a better hearing sensitivity and includes e.g. Clupeid species (sprat and herring). Species in the second group are less sensitive to noise and are represented by e.g. Salmonid fishes (salmon and trout).

To model the impact of piling noise on fish in the form of hearing impairment, threshold criteria were taken from an expert review by Popper *et al*. (2014). Based on it, TTS and recoverable injury threshold values are the same for the two groups of fish with a swim bladder.

The criterion for the behavioural reaction was taken from an investigation conducted by Hawkins *et al.* (2014), which is representative for fishes with the swim bladder involved in hearing.

It should be noted that studies of fish indicate that these organisms are able to rebuild hair cells responsible for receiving sound (e.g. Popper *et al.* 2014, Popper and Hawkins 2019). For this reason, the impact of noise on fish hearing is treated as a reversible phenomenon and thus, referred to as a recoverable injury.

A summary of the noise exposure criteria applied for fishes with a swim bladder is presented in the Table 3.3.

Table 3.3 Overview of the noise exposure criteria for fishes with a swim bladder used to calculate the impact ranges of piling noise

Source	Effect	Single strike / cumulative	Sound level type	Threshold	Unit
Popper *et al.* 2014	Recoverable Injury	cumulative	unweighted SEL	203	dB re. 1 $\mu Pa^2 s$
	TTS	cumulative	unweighted SEL	186	dB re. 1 $\mu Pa^2 s$
Hawkins *et al.* 2014	Behavioural	single strike	unweighted SEL	135	dB re. 1 $\mu Pa^2 s$

Farmed salmon and trout

The farmed species include Atlantic salmon, steelhead trout, sea trout or rainbow trout. In the following result sections, they are summarized and referred to as farmed salmon and trout.

Salmon and trout, belonging to the Salmonidae family, are considered fishes with a swim bladder not involved in hearing. Both species have relatively poor hearing abilities and lower sensitivity to noise compared to fishes with swim bladder involved in hearing (Hawkins and Johnstone 1978; Wysocki *et al.* 2007). Despite differences in sound perception of salmonids, according to Popper *et al.* (2014), threshold criteria for TTS and recoverable injury due to piling noise are the same for both groups of fish with a swim bladder. The respective thresholds are listed in Table 3.4.

To investigate the behavioural threshold of salmonid fish due to piling, a literature review of available studies has been conducted. Based on the review, it was found that salmonid fish, especially trout, show very limited reactions to piling noise, even in the short range from the sound source (Harding *et al.* 2016; Nedwell *et al.* 2003; Nedwell *et al.* 2006). Moreover, in neither of the available studies, the sound level which could be applied as a threshold value for the behavioural response of salmonids to the impulsive noise was indicated. Due to the lack of reliable data, a behavioural reaction criterion was not applied to model the impact of piling sounds on the farmed salmon and trout.

Table 3.4 Overview of the noise exposure criteria used to calculate impact ranges for the pile driving noise for the farmed salmon and trout

Source	Effect	Single strike / cumulative	Sound level type	Threshold	Unit
Popper *et al.* 2014	Recoverable Injury	cumulative	unweighted SEL	203	dB re. 1 $\mu Pa^2 s$
	TTS	cumulative	unweighted SEL	186	dB re. 1 $\mu Pa^2 s$

The fish cages are expected to be in depths between 20 m and 80 m below the sea surface. Therefore, the maximum SEL within these depths is considered for the evaluation of the impact on the farmed salmon and trout.

3.3.2 Threshold values used for continuous noise

Harbour porpoises and seals

For continuous noise, criteria for the hearing impairment of harbour porpoise were based on NMFS (2024).

The threshold for adverse behavioural response for harbour porpoises was taken from a review by Southall *et al.* (2007).

In the case of seals, there is not enough information to define a criterion for behavioural response to operational noise exposure.

A summary of the applied noise criteria for continuous noise is shown in Table 3.5.

Table 3.5 Overview of the noise exposure criteria for marine mammals used for the calculation of impact ranges for continuous noise

Source	Effect	Marine mammal species	Maximum / cumulative	Sound level type	Threshold Level	Unit
NMFS 2024	AUD INJ	Harbour porpoise	Cumulative	VHF-weighted SEL	181	dB re. 1 µPa^{2}s
	TTS	Harbour porpoise	Cumulative	VHF-weighted SEL	161	dB re. 1 µPa^{2}s
NMFS 2024	AUD INJ	Harbour and grey seal	Cumulative	PW-weighted SEL	195	dB re. 1 µPa^{2}s
	TTS	Harbour and grey seal	Cumulative	PW-weighted SEL	175	dB re. 1 µPa^{2}s
Southall et al. 2007	Adverse behavioural response	Harbour porpoise	Maximum	Unweighted SPL	140	dB re 1 µPa

Fishes with a swim bladder

For fish with the swim bladder involved in hearing, the noise exposure criteria for TTS and recoverable injury due to continuous noise were taken from a review by Popper *et al*. (2014). These criteria were set based on extended exposure durations of 48 h and 12 h. It should be noted that such continuous exposure is unlikely to occur in natural conditions. This prolonged exposure could be relevant for the farmed salmon and trout. However, these thresholds were derived from studies on goldfish (Amoser and Ladich 2003; Smith *et al.* 2006), a species with higher hearing sensitivity than most fish found in the assessment area (including farmed salmon and trout which do not have swim bladders involved in hearing). The criteria do not consider the potential mobility of wild fishes, which would likely not result in a continuous noise exposure over 12 h or 48 h. Therefore, these criteria should be regarded as highly conservative. Due to the current lack of alternative criteria that better reflect local ecological conditions, these thresholds should not be treated as strict regulatory conditions but rather as precautionary reference points for the purposes of this assessment.

A summary of thresholds applied for the wild fish is presented in the Table 3.6

Table 3.6 Overview of the noise exposure criteria for fishes with the swim bladder involved in hearing used to calculate impact ranges for the continuous noise

Source	Effect	Maximum / cumulative	Sound level type	Threshold Level	Unit
Popper *et al*. 2014	Recoverable Injury	Maximum	Unweighted SPL	170 (48 h)	dB re 1 µPa
	TTS	Maximum	Unweighted SPL	158 (12 h)	dB re 1 µPa

No criteria for recoverable injury and TTS are available for fishes without the swim bladder involved in hearing (e.g. salmon and trout). As a precautionary measure, the above-mentioned thresholds for the species with a swim bladder involved in hearing (see Table 3.6) were applied. These criteria are preliminary and should be revised when new studies and species-specific data become available.

Based on the available literature, no noise criteria could be established for behavioural changes due to continuous noise, including that from operating offshore wind farms. There is very little information on the topic, and in a few cases, there were methodological flaws. For example, van der Knaap *et al.* (2022) conducted experiments in small net pens only a few meters wide, limiting fish movement and potentially affecting behaviour. Several authors (e.g., Popper *et al.* (2020)) have noted that such confined setups may not allow fish to exhibit natural responses, raising questions about the suitability of these methods. It is noteworthy that these limitations persist in some recent studies. A study by Oppedal *et al.* (2025) investigated sound exposure effects on salmon and suggested a stress response that could potentially impact life fitness. However, the study did not allow for threshold identification due to methodological issues, including the lack of a control group and the use of small tanks, which may have introduced confounding variables and affected sound propagation. At the same time, studied literature has shown that long-term exposure of farmed salmonid fish to sounds generated by the aquaculture systems does not affect the growth and fitness of hatched individuals (Barrett and Oppedal 2025; Davidson *et al.* 2009; Slater *et al.* 2020; Wysocki *et al.* 2007). Available studies suggest that farmed salmonids habituate to ambient noise levels and therefore, in the long run, do not show a stress response to continuous sounds. Based on that, within the evaluation of the impact of continuous noise on fishes with the swim bladder involved in hearing, a behavioural threshold could not be applied in the modelling.

The review of criteria and studies conducted to develop the applied methodology revealed several data gaps and uncertainties. In some cases, due to limited data, certain potential effects on fishes could not be evaluated. In the spirit of developing a methodology that best reflects real-world conditions and addresses existing knowledge gaps, we propose recommendations for future work.

The identified gaps in knowledge and uncertainties largely fall within the following domains:

- Lack of species-specific criteria
- Lack of criteria considering fishes' mobility
- Methodological limitations within existing studies, preventing their results from being used as reliable criteria
- An insufficient number of species-specific studies, making it insufficient to establish some criteria.

The more in detail information on the identified knowledge gaps, the approaches applied, their potential consequences, and recommendations to address the data gaps are presented in Table B-1.

The fish cages are expected to be in depths between 20 m and 80 m below the sea surface. Therefore, the maximum SEL within these depths is considered for the evaluation of the impact on the farmed salmon and trout.

3.3.3 Effective quiet – mammals

An important concept considered in this study is the 'effective quiet', defined by Finneran (2015) as the highest SPL that would not produce a significant TTS or affect recovery from a TTS produced by a prior, higher-level exposure. The same work indicates that this value could be 124 dB re 1 μPa for the harbour porpoise and cites the study by Kastelein *et al.* (2002) in support of this conclusion. However, that study did not directly investigate into the 'effective quiet'. Yet, since the 124 dB re 1 μPa is the lowest sound level so far measured, leading to TTS in harbour porpoises. It can, therefore, be viewed as a preliminary value until more solid data is available.

Effective quiet is applied to the one-third octave bands. Whenever the unweighted SPL of a band is below 124 dB, it is neglected in the summation of the acoustical energy to the broadband SEL.

Effective quiet is applied to the acoustical results for impulsive and continuous noise. In the case of impulsive noise, the SPL is estimated by adding a constant conversion factor to the SEL. Frequency weighting is conducted afterwards with the remaining bands.

4 Acoustic Results

The acoustical results of the different scenarios are presented in the form of noise maps. These are shown in combination with the respective impact areas. Within the noise maps that present unweighted SEL levels only the sound levels that are above the considered ambient noise level are shown to represent the detectable acoustic footprint of the considered activity.

The contour of the behavioural impact areas follows the same contour as the respective noise results. Impact areas derived with cumulative thresholds cannot directly be compared to the sound maps as cumulation over time is influenced by several factors such as the number of noise events, the strength of the individual events, and if applicable, moving receivers, and effective quiet.

Within Figure 4.1 an overview of the considered turbine (yellow dots) and fish farm (pink dots) locations as well as the considered pile driving and suction anchoring location (in red) is provided together with the two adjacent Natura 2000 areas.

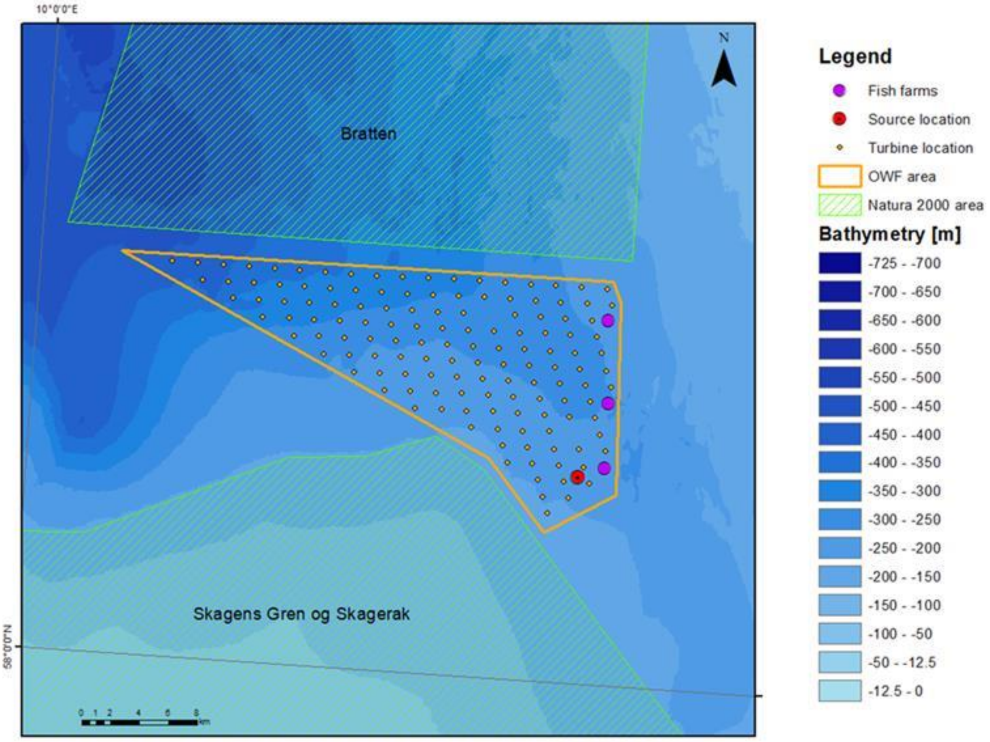

Figure 4.1 Map of the turbine, fish farm locations and the modelled source location within the Mareld OWF area

4.1 Underwater noise from the wind farm installation - Pile Driving

The underwater noise from pile driving was modelled with and without noise mitigation. The results for both scenarios are described in the following. The unmitigated scenario is provided for reasons of completeness only since the latest Natura 2000 permit for the Mareld OWF specifies that pile driving is only allowed with the application of noise mitigation systems. (Lännsstryelsen Västra Götaland 2025).

4.1.1 Unmitigated scenario

The single-strike SEL for unmitigated pile driving is shown in Figure 4.2. Furthermore, the contour of the bathymetry, the neighbouring Natura 2000 areas and four out of the 72 modelled transects are highlighted. The vertical results of these four transects are displayed within the appendix in Figure C-1.

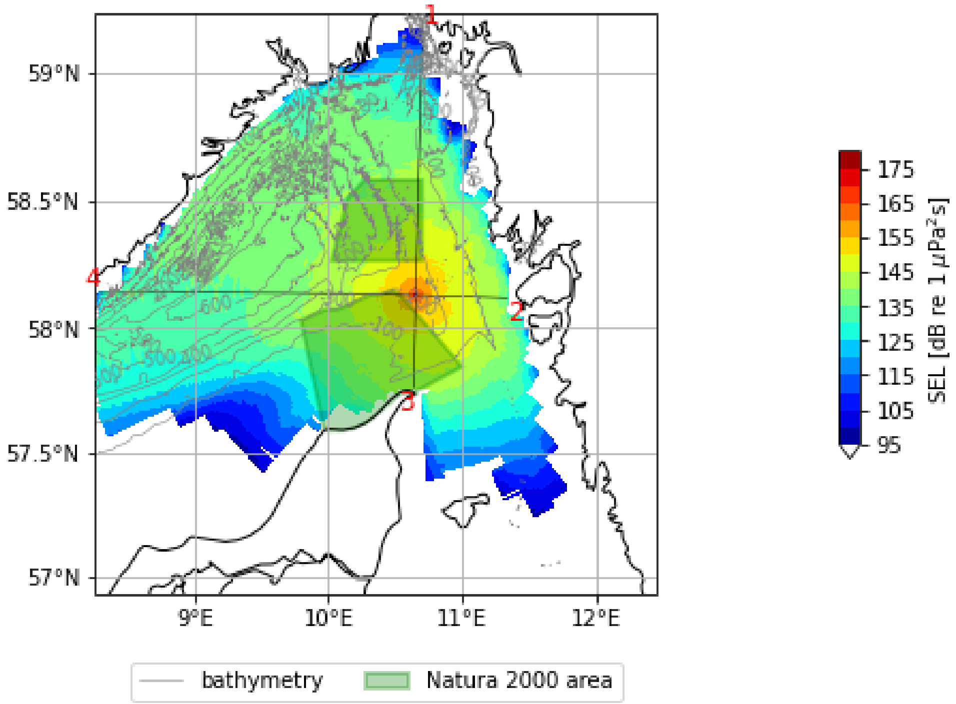

Figure 4.2 Map of the unweighted single-strike SEL at the Mareld OWF caused by unmitigated pile driving

Only levels above the ambient noise are shown. The black numbered lines indicate the transects shown in **Figure C-1 The unweighted SEL over depth and range for the four transect cuts shown in Figure 4.2 resulting from the unmitigated pile driving in the Mareld OWF**

Only levels above the ambient noise are shown**.**Figure C-1.

Harbour porpoise

Harbour porpoises are expected to exhibit a behavioural response to the unmitigated pile driving noise at a maximum range of almost 63 km from the source location, with this effect covering an area of 7551 km². The behavioural impact area and the SPL_{125ms} are displayed in Figure 4.3. The map clearly shows that the respective impact area covers the entire Bratten Natura 2000 area and large parts of the Skagens Gren og Skagerak Natura 2000 area.

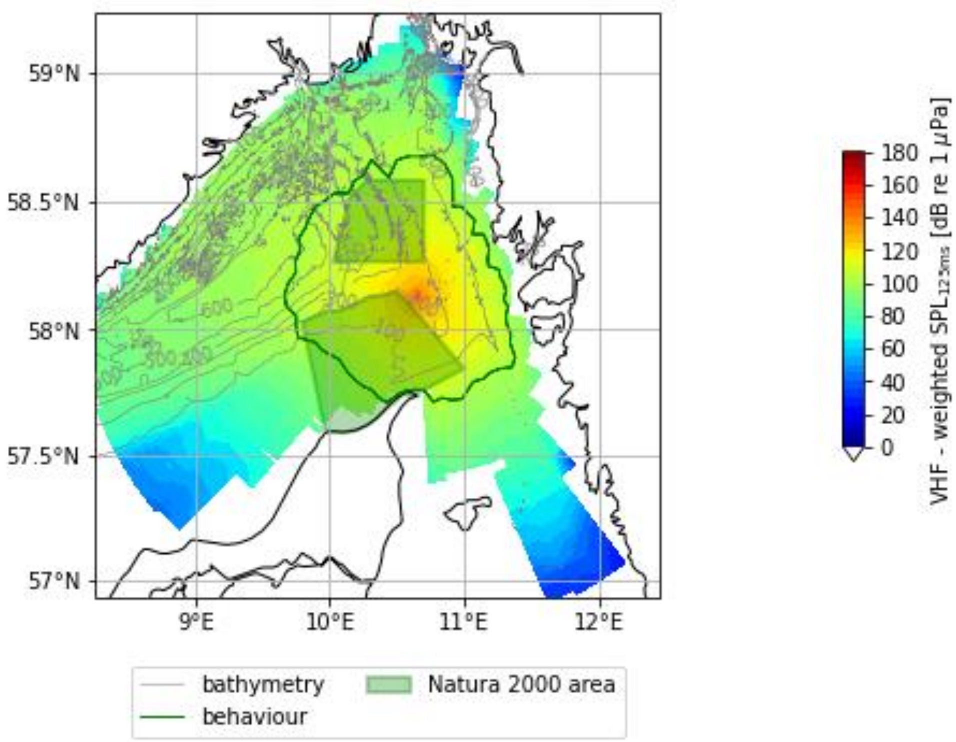

Figure 4.3 Map of the single-strike VHF-weighted SPL_{125ms} at the Mareld OWF resulting from unmitigated pile driving and the impact area for behavioural response of the harbour porpoise

The maximum impact range for TTS is around 10 km and the impact area covers 255 km². AUD INJ is expected only close to the piling site with a maximum range of 200 m and the impact area of 0.09 km². Both hearing impairment impact areas and the VHF-weighted SEL are shown in Figure 4.4. Table 4.1 Depending on the actual piling location, an overlap of the TTS impact area with one of the Natura 2000 areas is expected.

The TTS and AUD INJ impact areas derived with the SEL_{cum} criterion are greater than the ones derived with the SPL_{peak} criterion. Therefore, noise maps for the SPL_{peak} results are not presented, and the corresponding impact ranges and areas are summarized within Table 4.1.

For all investigated effects the minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.1.

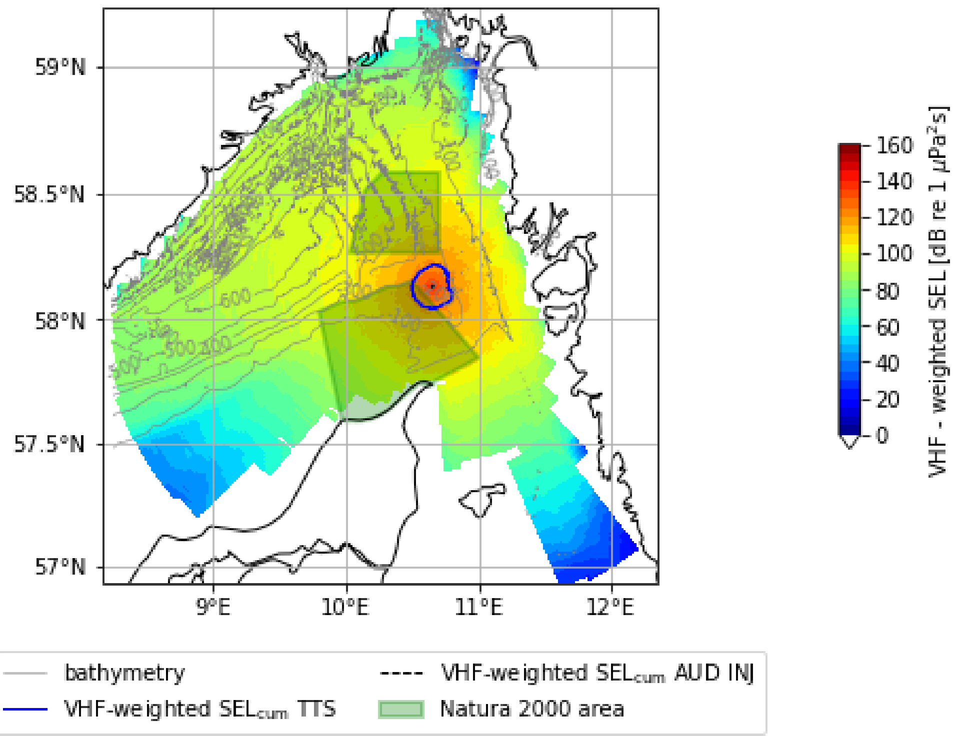

Figure 4.4 **Map of the single-strike VHF-weighted SEL at the Mareld OWF resulting from unmitigated pile driving and the impact areas for auditory injuries of the harbour porpoises**

Table 4.1 **The minimum, average and maximum range of behavioural, TTS and AUD INJ impact areas for the harbour porpoise in dependence on the definition of the thresholds for the unmitigated pile driving noise scenario**

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
Behaviour	VHF-weighted SPL_{125ms}	33.7	48.4	62.7	7551
TTS	SPL_{peak}	0.3	0.4	0.4	0.4
	VHF-weighted SEL_{cum}	6.7	9.0	10.1	255
AUD INJ	SPL_{peak}	0.1	0.1	0.1	0.03
	VHF-weighted SEL_{cum}	0.1	0.2	0.2	0.09

Seals

Seals are expected to exhibit a behavioural response to the unmitigated pile driving noise at a maximum range of 6.3 km from the source location, with this effect covering an area of 58 km². The respective impact area covers only a very small part of the Skagens Gren og Skagerak Natura 2000 area as shown in the single-strike SEL map in Figure 4.5.

The TTS and AUD INJ impact areas derived with the SEL_{cum} criterion are greater than the ones derived with the SPL_{peak} criterion. Therefore, the SPL_{peak} results are only reported within Table 4.2.

The maximum impact range for TTS is around 43 km and the impact area covers 3467 km². AUD INJ is expected to have a maximum range of nearly 6 km and the impact area of approximately 80 km².

Depending on the actual piling location, an overlap of the TTS impact area with one of the Natura 2000 areas can be expected. This is also shown in Figure 4.6, where the hearing impairment impact areas and the single strike PW-weighted SEL are shown.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.2.

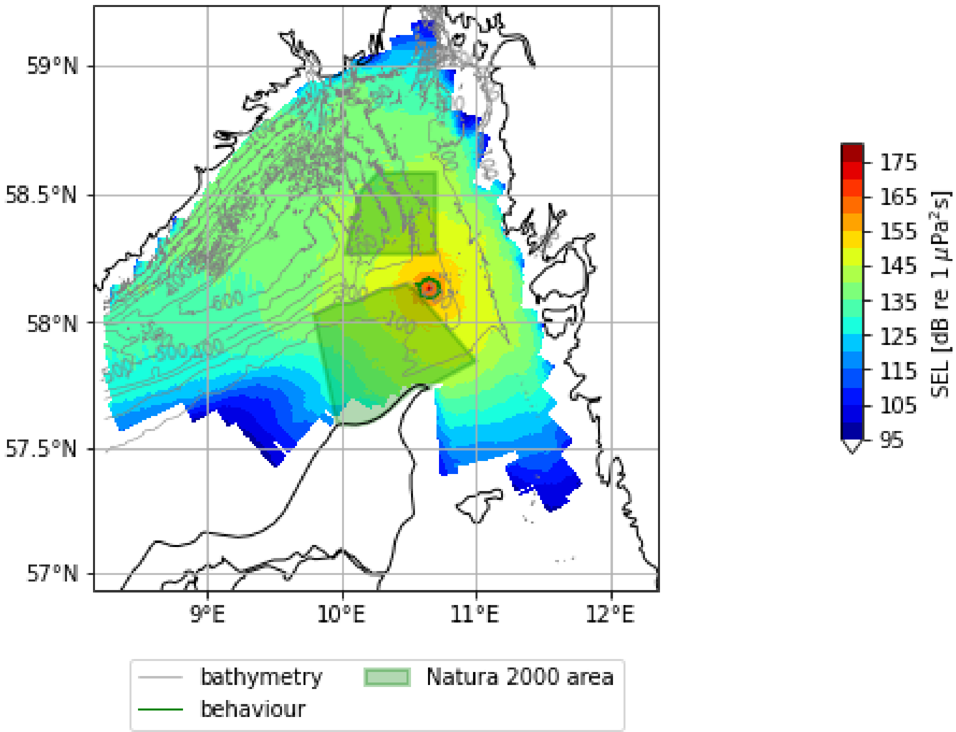

Figure 4.5 Map of the single-strike unweighted SEL at the Mareld OWF resulting from unmitigated pile driving and the impact areas for behavioural response of seals

Only sound levels above the ambient noise level are displayed.

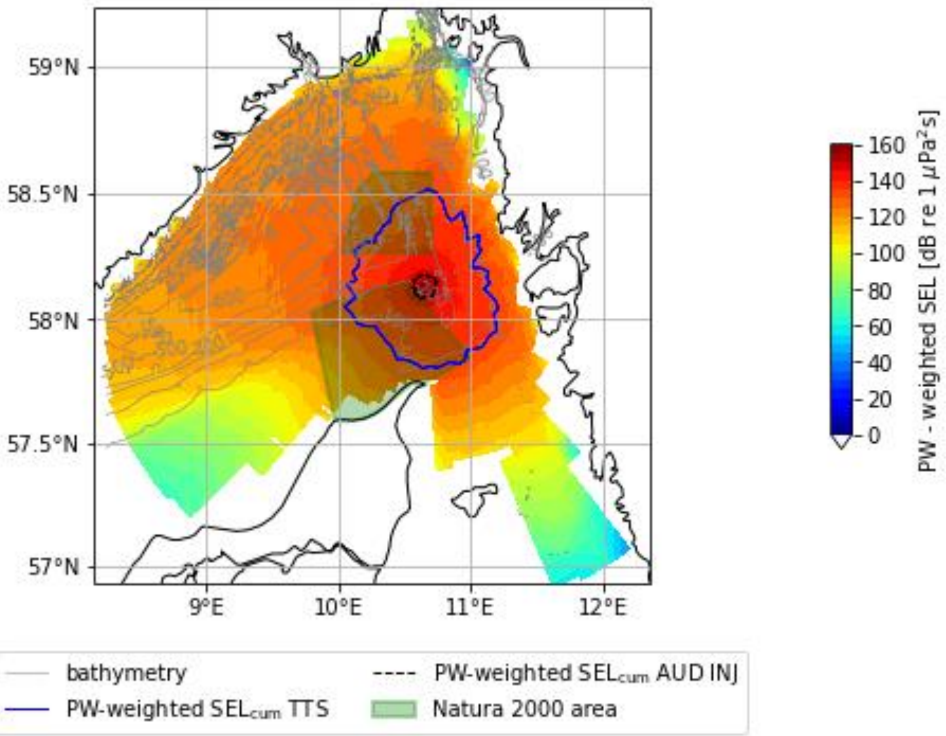

Figure 4.6 Map of the single-strike PW-weighted SEL at the Mareld OWF resulting from unmitigated pile driving and the impact areas for auditory injuries of seals

Table 4.2 The minimum, average and maximum range of behavioural TTS and AUD INJ impact areas for harbour and grey seal in dependence on the definition of the thresholds for the unmitigated pile driving noise scenario

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
Behaviour	SEL	3.8	4.3	6.3	58.0
TTS	SPL_{peak}	0.1	0.1	0.1	0.03
	PW-weighted SEL_{cum}	21.8	33.0	43.2	3467
AUD INJ	SPL_{peak}	0.1	0.1	0.1	0.03
	PW-weighted SEL_{cum}	3.9	5.0	5.9	79.5

Fishes with a swim bladder

Fishes with the swim bladder involved in hearing are expected to exhibit a behavioural response to the unmitigated pile driving noise at a maximum range of 116 km from the source location, with this effect covering an area of 13416 km^2. The impact area covers the Bratten Natura 2000 and large parts of the Skagens Gren og Skagerak Natura 2000 area. The maximum TTS impact range is 22 km, and the area extends over 1014 km^2 and covers parts of both Natura 2000 areas. The recoverable injury extends up to a maximum range of 900 m, leading to an impact area of 2.2 km^2. All three impact areas are shown in Figure 4.7 together with the single-strike SEL.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.3.

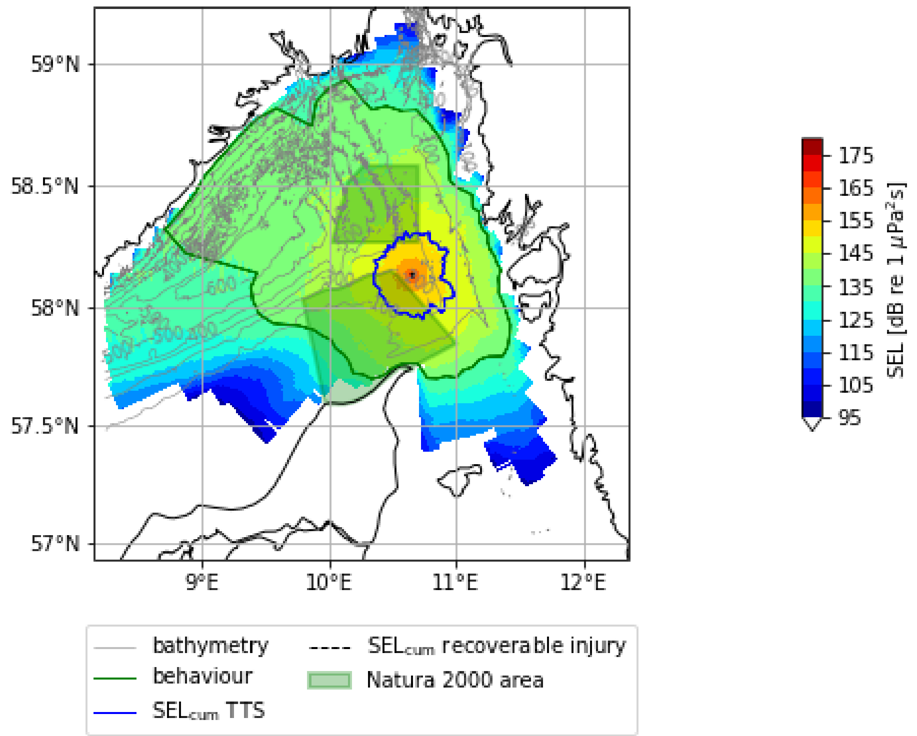

Figure 4.7 **Map of the single-strike unweighted SEL at the Mareld OWF resulting from unmitigated pile driving and the impact areas for hearing impairment and behavioural impacts of fish with swim bladder involved in hearing**
Only sound levels that are above the ambient noise level are displayed.

Table 4.3 **The minimum, average and maximum range of behavioural, TTS and recoverable injury impact areas for fishes with the swim bladder involved in hearing in dependence on the definition of the thresholds for the unmitigated pile driving noise scenario.**

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km²]
Behaviour	SEL	38	61.4	116	13416
TTS	SEL_{cum}	13.1	17.9	21.8	1014
Recoverable injury	SEL_{cum}	0.7	0.8	0.9	2.2

Farmed salmon and trout

TTS and Recoverable Injury ranges are evaluated for the farmed salmon and trout at the planned depth of the cages in the water column. These are supposed to be between 20 m and 80 m below the sea surface. The maximum range of the TTS result is around 17 km, which is about 5 km lower than the results derived when the SEL was evaluated over the full water column. The maximum range for the recoverable injury is 800 m. The maximum SEL evaluated between 20 m and 80 m below the sea surface is displayed together with the TTS and recoverable injury impact areas in Figure 4.8.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.4.

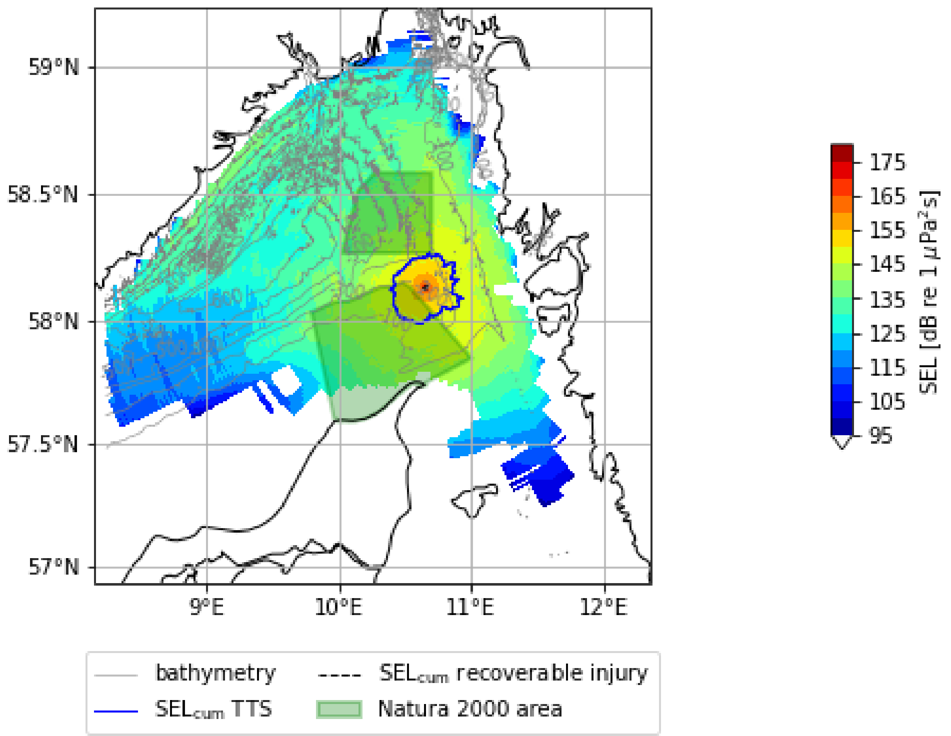

Figure 4.8 Map of the single-strike unweighted SEL at the Mareld OWF resulting from unmitigated pile driving and the impact areas for hearing impairment of the farmed fishes
Only the acoustical results in depths between 20 and 80 m were considered and only sound levels that are above the ambient noise level are displayed.

Table 4.4 The average and maximum range of TTS and Recoverable Injury for the farmed fish species.
Only the acoustical results in depths between 20 and 80 m were considered.

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
TTS	SEL_{cum}	11.6	14.4	17.3	659
Recoverable Injury	SEL_{cum}	0.7	0.8	0.8	1.9

4.1.2 Mitigated scenario

The single-strike SEL for mitigated pile driving is shown in Figure 4.9. Furthermore, the contour of the bathymetry, the neighbouring Natura 2000 areas and four out of the 72 modelled transects are highlighted. The vertical results of these four transects are displayed in the appendix in Figure C-2. The implemented mitigation measure was the Hydro Sound Damper (HSD) system. More information about the applied mitigation can be found in the Appendix A.

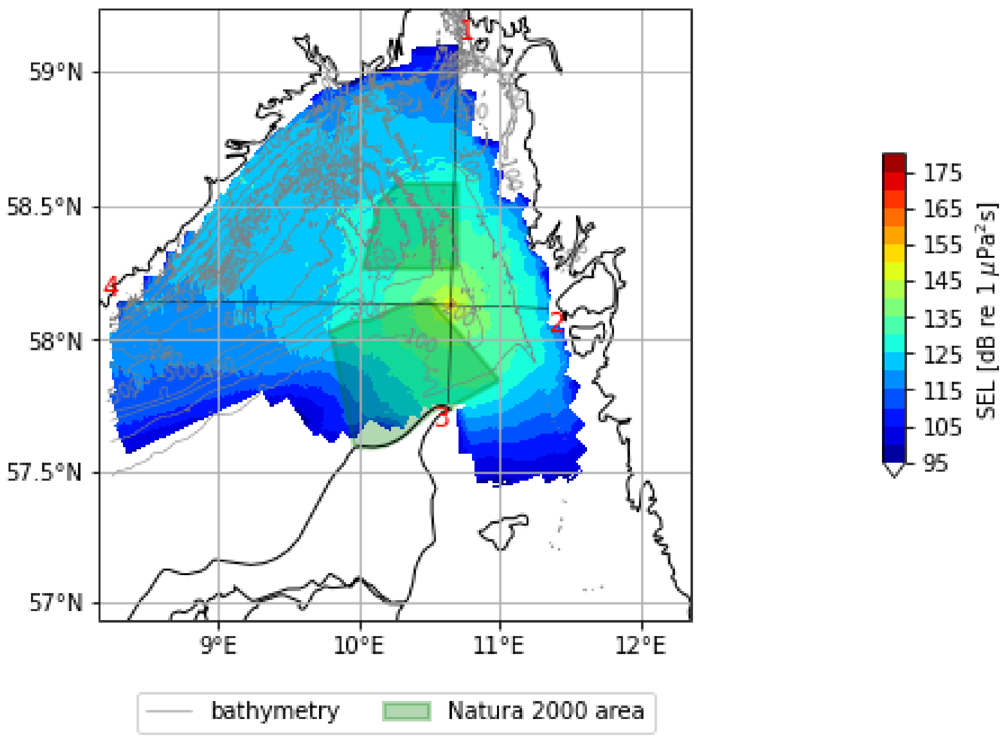

Figure 4.9 Map of the unweighted single-strike SEL at the Mareld OWF caused by mitigated pile driving
Only levels above the ambient noise are shown. The black numbered lines indicate the transects shown in Figure C.1.

Harbour porpoise

Harbour porpoises are expected to exhibit a behavioural response to the mitigated pile driving noise at a maximum range of almost 14 km from the source location, with this effect covering an area of 414 km². The behavioural impact area and the SPL_{125ms} are displayed in Figure 4.10. The map clearly shows that the respective impact area covers only parts of the Skagens Gren og Skagerak Natura 2000 area.

The TTS and AUD INJ impact areas derived with the SEL_{cum} criterion are greater than the ones derived with the SPL_{peak} criterion. Therefore, noise maps for the SPL_{peak} results are not presented, and the corresponding impact ranges and areas are summarized within Table 4.5.

The maximum impact ranges for TTS and AUD INJ are 100 m and the impact areas cover 0.09 km². This is the case for the SPL_{peak} as well as the SEL_{cum} criterion. Both hearing impairment impact areas and the VHF-weighted SEL are shown in Figure 4.11. No overlap of the impact areas and the Natura 2000 areas is expected.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.5.

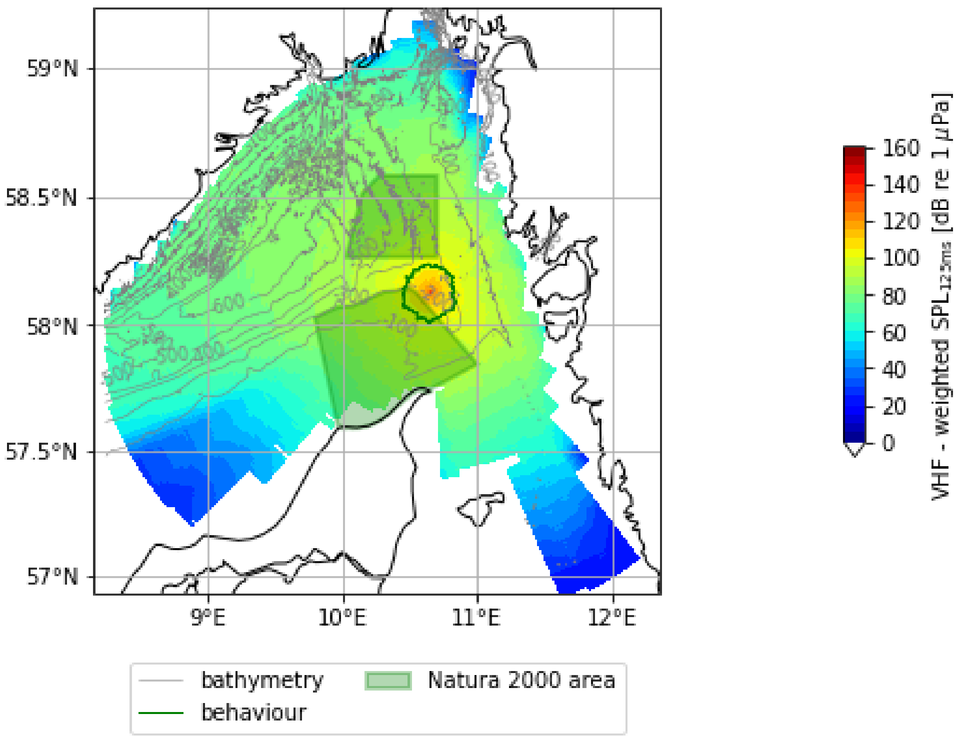

Figure 4.10 **Map of the single-strike VHF-weighted SPL_{125ms} at the Mareld OWF resulting from mitigated pile driving and the impact area for a behavioural response of the harbour porpoise**

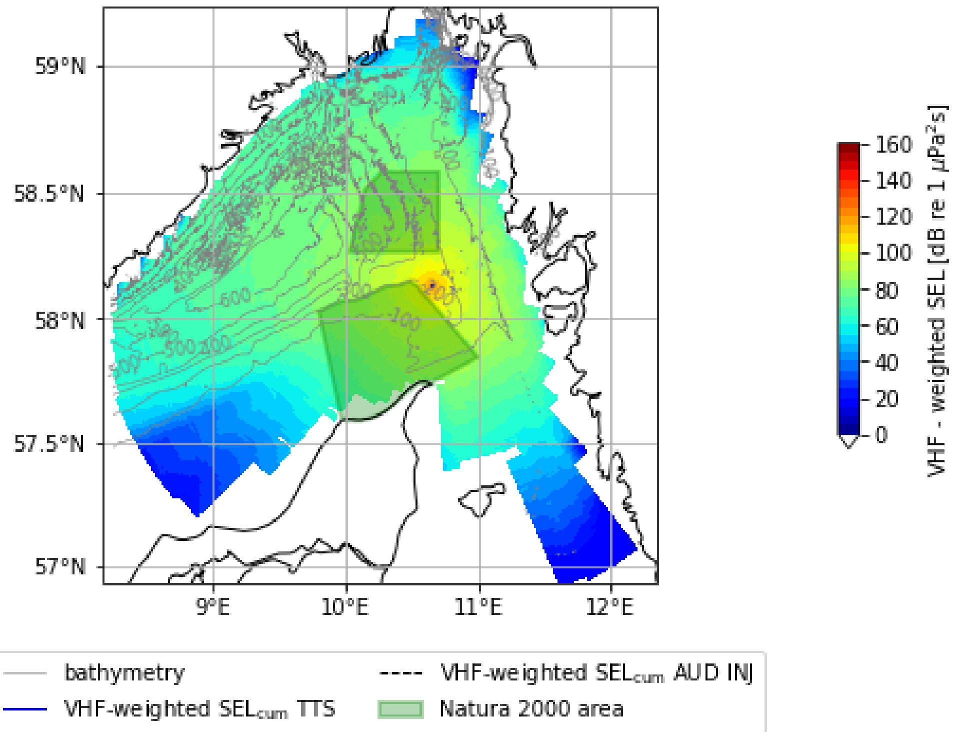

Figure 4.11 **Map of the single-strike VHF-weighted SEL at the Mareld OWF resulting from mitigated pile driving and the impact areas for auditory injuries of the harbour porpoise**

Table 4.5 **The minimum, average and maximum range of behavioural TTS and AUD INJ impact areas for the harbour porpoise in dependence on the definition of the thresholds for the mitigated pile driving noise scenario**

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
Behaviour	VHF-weighted SPL_{125ms}	9.3	11.4	13.7	414
TTS	SPL_{peak}	0.1	0.1	0.1	0.03
	VHF-weighted SEL_{cum}	0.1	0.1	0.1	0.03
AUD INJ	SPL_{peak}	0.1	0.1	0.1	0.03
	VHF-weighted SEL_{cum}	0.1	0.1	0.1	0.03

Seals

Seals are expected to exhibit a behavioural response to the mitigated pile driving noise at a maximum range of 400 m from the source location, with this effect covering an area of 0.3 km^2. The respective impact area does not interfere with any of the two Natura 2000 areas as shown in the single-strike SEL map in Figure 4.12.

The TTS and AUD INJ impact areas derived with the SEL_{cum} criterion are greater than the ones derived with the SPL_{peak} criterion. Therefore, the SPL_{peak} results are only reported within Table 4.6.

The maximum impact range for TTS is around 3.7 km and the impact area covers approximately 28 km^2. AUD INJ is expected to have a maximum range of 100 m. Depending on the actual piling location, an overlap of the TTS impact area with one of the Natura 2000 areas may occur. This is also shown in Figure 4.13, where the hearing impairment impact areas and the single strike PW-weighted SEL are shown.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.6.

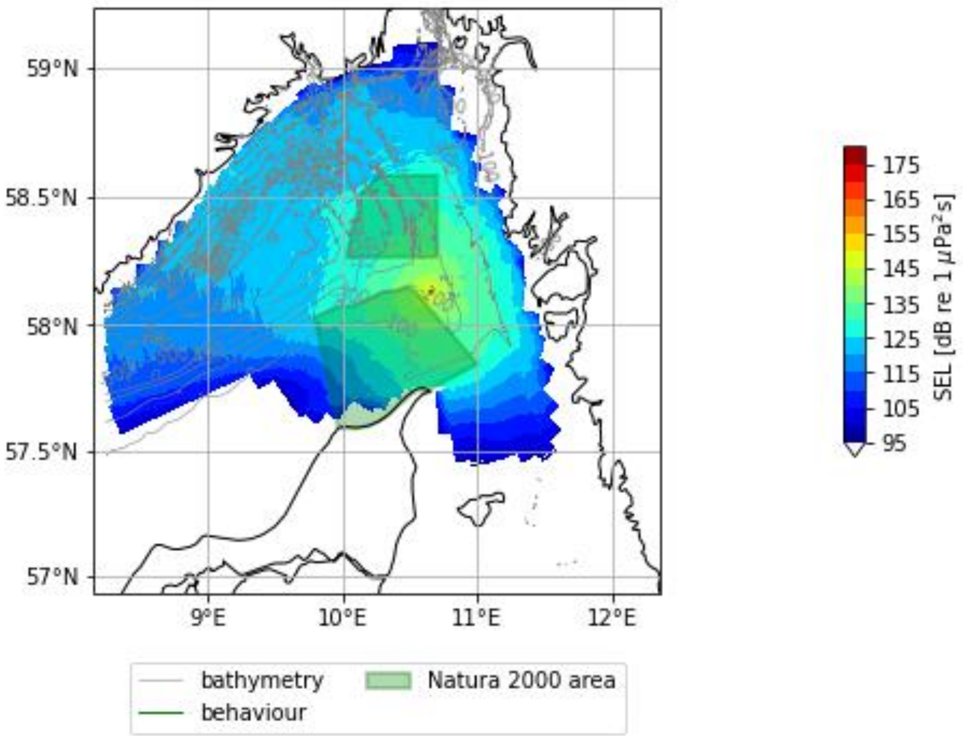

Figure 4.12 Map of the single-strike unweighted SEL at the Mareld OWF resulting from mitigated pile driving and the impact areas for a behavioural response of seals

Only sound levels above the ambient noise level are displayed.

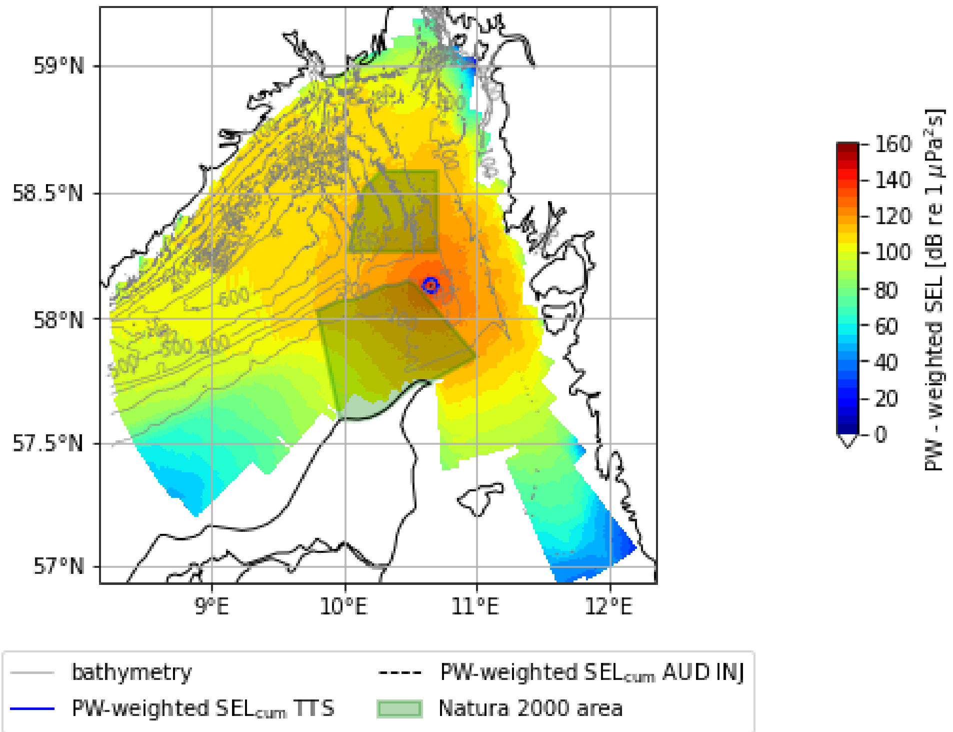

Figure 4.13 Map of the single-strike PW-weighted SEL at the Mareld OWF resulting from mitigated pile driving and the impact areas for auditory injuries of seals

Table 4.6 **The minimum, average and maximum range of behavioural TTS and AUD INJ impact areas for harbour and grey seal in dependence on the definition of the thresholds for the mitigated pile driving noise scenario**

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
Behaviour	SEL	0.3	0.3	0.4	0.3
TTS	SPL_{peak}	0.1	0.1	0.1	0.03
	PW-weighted SEL_{cum}	2.7	3.0	3.7	28.2
AUD INJ	SPL_{peak}	0.1	0.1	0.1	0.03
	PW-weighted SEL_{cum}	0.1	0.1	0.1	0.03

Fishes with a swim bladder

Fishes with the swim bladder involved in hearing are expected to exhibit a behavioural response to the mitigated pile driving noise at a maximum range of 19.4 km from the source location, with this effect covering an area of 887 km^2. The impact area covers parts of the Bratten Natura 2000 and the Skagens Gren og Skagerak Natura 2000 area. The maximum TTS impact range is 1.3 km and the area extends over 4.4 km^2 not interfering with a Natura 2000 area. Recoverable injury is only expected in the direct vicinity of the pile (<100m), corresponding to an impact area of 0.03 km^2. All three impact areas are shown in Figure 4.14 together with the single-strike SEL.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.7Table 4.3.

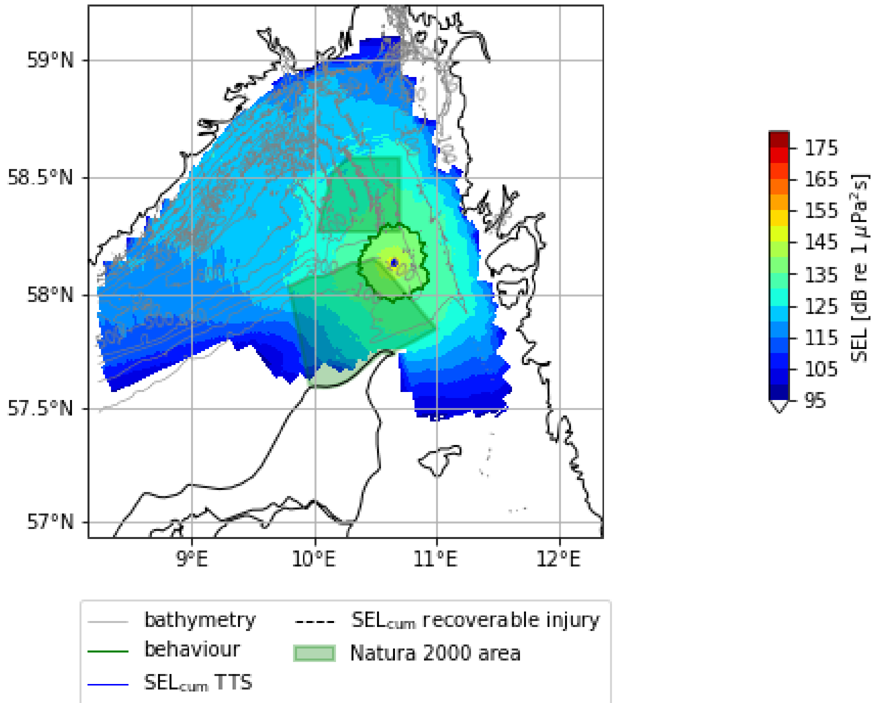

Figure 4.14 **Map of the single-strike unweighted SEL at the Mareld OWF resulting from mitigated pile driving and the impact areas for hearing impairment and behavioural impacts of fish with swim bladder involved in hearing**

Only sound levels above the ambient noise level are displayed.

Table 4.7 The minimum, average and maximum range of behavioural TTS and recoverable injury impact areas for fishes with a swim bladder in dependence on the definition of the thresholds for the mitigated pile driving noise scenario

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
Behaviour	SEL	13.2	16.7	19.4	887
TTS	SEL_{cum}	1.0	1.2	1.3	4.4
Recoverable injury	SEL_{cum}	0.1	0.1	0.1	0.03

Farmed salmon and trout

The maximum range of the TTS result is 1.3 km. The maximum range for the recoverable injury is 100 m. The maximum SEL evaluated between 20 m and 80 m below the sea surface is displayed together with the TTS and recoverable injury impact areas in Figure 4.15.

All minimal, mean, and maximum impact ranges as well as the area are provided in Table 4.8. Despite the one mitigation scenario derived with the HSD insertion loss, results derived with a more general mitigation approach applying broadband reductions between 5 dB and 20 dB are listed therein. These reductions could either be achieved with noise mitigation systems or with the reduction of the number of strikes and the strike energy.

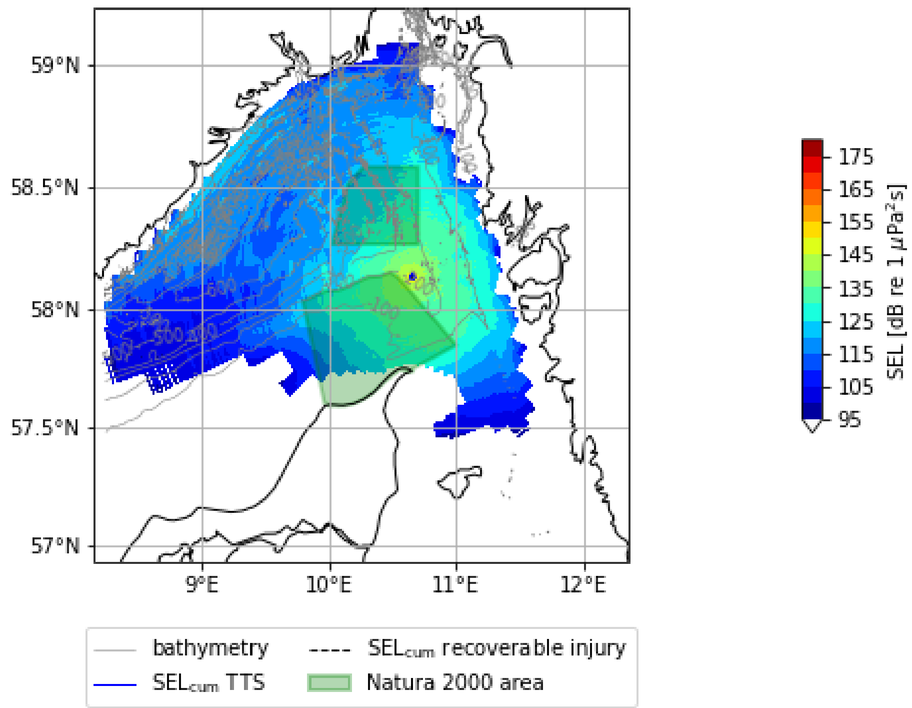

Figure 4.15 Map of the single-strike unweighted SEL at the Mareld OWF resulting from mitigated pile driving with the application of an HSD and the impact areas for hearing impairment of the farmed fish

Only the acoustical results in depths between 20 and 80 m were considered and only sound levels that are above the ambient noise level are displayed.

Table 4.8 **The average and maximum range of TTS and Recoverable Injury for the farmed fish species**

Only the acoustical results in depths between 20 m and 80 m below the sea surface were considered.

Effect	Reduction	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
TTS	HSD (-14.9 dB)	1.0	1.2	1.3	4.2
Recoverable Injury	HSD (-14.9 dB)	0.1	0.1	0.1	0.03
TTS	-5 dB	5.3	6.4	7.9	132
Recoverable Injury	-5 dB	0.3	0.3	0.3	0.3
TTS	-10 dB	2.4	2.6	2.9	21.5
Recoverable Injury	-10 dB	0.1	0.1	0.1	0.03
TTS	-15 dB	0.9	1.0	1.2	3.6
Recoverable Injury	-15 dB	0.1	0.1	0.1	0.03
TTS	-20 dB	0.4	0.4	0.4	0.5
Recoverable Injury	-20 dB	0.1	0.1	0.1	0.03

4.2 Underwater noise from the aquaculture installation – Suction anchor

The acoustical footprint of the suction anchor installation is shown within Figure 4.16.

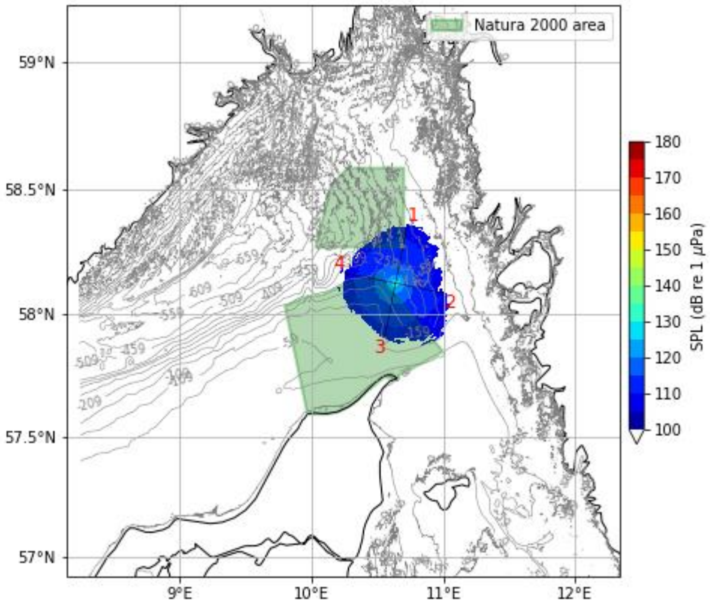

Figure 4.16 Map of the unweighted SPL at the Mareld OWF caused by suction anchor installation that are above the ambient noise level
The black numbered lines indicate the transects shown in Figure C-3

Harbor porpoise

The behavioural as well as TTS maximum impact range is below 100 m for harbour porpoise and therefore not well visible within Figure 4.17 and Figure 4.18. Furthermore, an overlapping influence of the impact areas with any of the neighbouring Natura 2000 sites can also be ruled out.

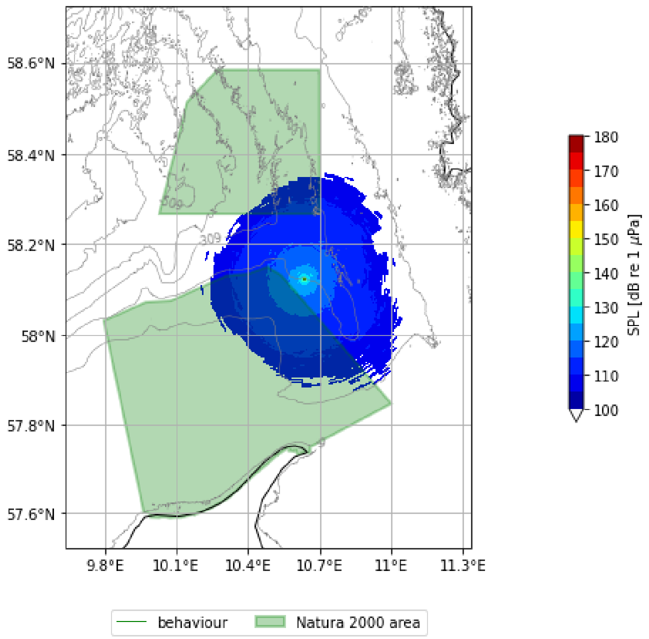

Figure 4.17 Map of the unweighted SPL at the Mareld OWF resulting out of suction anchor installation work with the behavioural impact area for harbour porpoises

The impact area is very small with a radius of 100 m around the source location and therefore not well visible. Only sound levels above the ambient noise are shown.

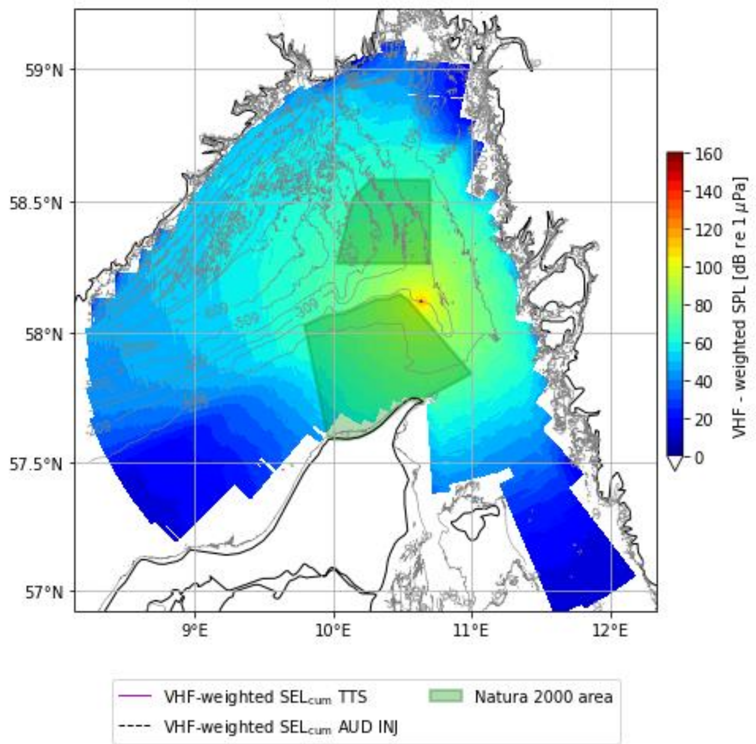

Figure 4.18 Map of the VHF-weighted SPL at the Mareld OWF resulting out of suction anchor installation work with the TTS impact area for harbour porpoises

The impact area is very small with a radius of 100 m around the source location and therefore not well visible.

Seals

Since the source level of the work is already below the thresholds, no further evaluation has been conducted.

Fishes with the swim bladder involved in hearing

The modelling results show that for fishes with the swim bladder involved in hearing, the emitted noise of the suction anchor installation is expected to result in TTS only up to a range of 100 m from the sound source. The acoustical footprint and the TTS impact area are displayed in Figure 4.19. The respective minimal, mean, and maximum impact ranges as well as the impact area are listed in Table 4.9.

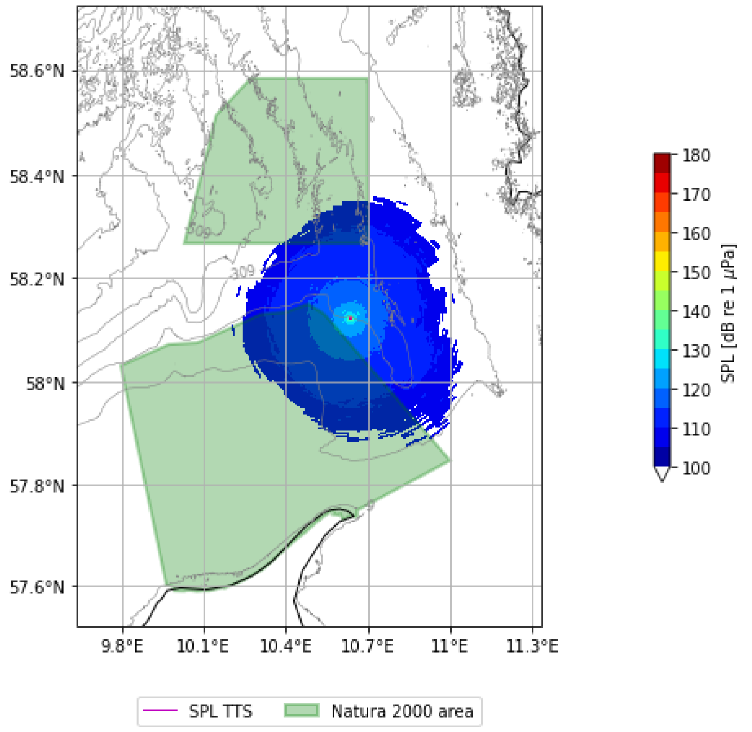

Figure 4.19 Map of the unweighted SPL at the Mareld OWF resulting out of suction anchor installation work with the TTS impact area for fishes with the swim bladder involved in hearing The impact area is very small with a radius of 100 m for TTS. Only sound levels above the ambient noise are shown.

Table 4.9 The average and maximum range of the TTS impact for fish with the swim bladder involved in hearing

Effect	Threshold type	Minimum range [km]	Average range [km]	Maximum range [km]	Impact area [km^2]
TTS	SPL	0.1	0.1	0.1	0.03

Farmed salmon and trout

The modelling results for farmed salmon and trout also indicate that TTS is not expected at ranges further than 100 m. The SPL evaluated between 20 m to 80 m below the sea surface is shown in Figure 4.20.

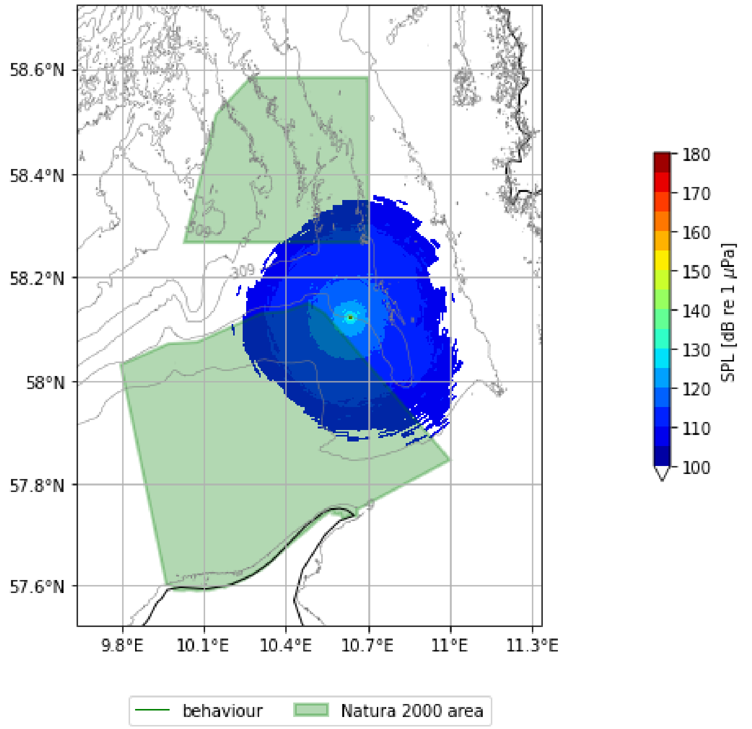

Figure 4.20 Map of the unweighted SPL at the Mareld OWF resulting out of suction anchor installation work with the TTS impact area for the farmed fish

The impact area is very small with a radius of 100 m around the source location and therefore not well visible. Only the acoustical results in depths between 20 and 80 m were considered and only sound levels that are above the ambient noise level are displayed.

4.3 Underwater noise from operation and maintenance

4.3.1 Operational noise from the floating wind turbines and aquaculture

The operational noise of the floating turbines alone and the combined noise of the floating turbines and the fish farms are shown in Figure 4.22. A zoomed version of the maps is provided in Figure 4.22. Only minor differences were observed at the three eastern fish farm positions. Therefore, subsequent analyses focus on noise maps and impact areas from the combined wind turbine and aquaculture scenario.

The operational underwater noise from the wind turbines and the aquaculture is leading to a noise field with several sources. Since the combined levels do not lead to impact areas overlapping multiple sources, several small impact zones are derived. In order to get an impact range, the total impacted area is converted into an effective radius. This is done by dividing the total area with the number of turbines and assuming the area to be of circular shape

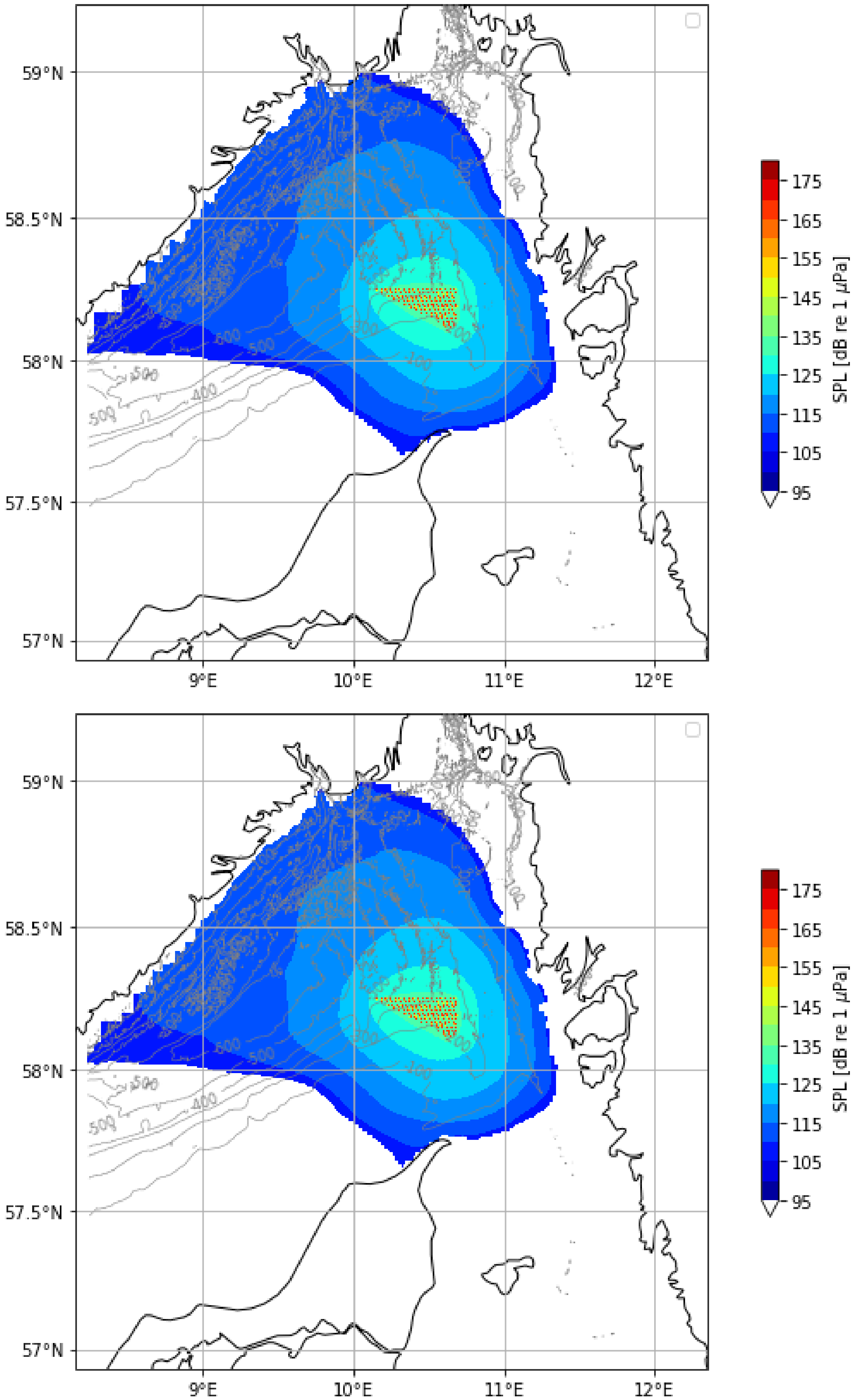

Figure 4.21 Map of the unweighted SPL at the Mareld OWF caused by the operation of the floating wind turbines (upper) and the combination of the operational noise from the fish and the wind farm (lower)

Only levels above the ambient noise are shown.

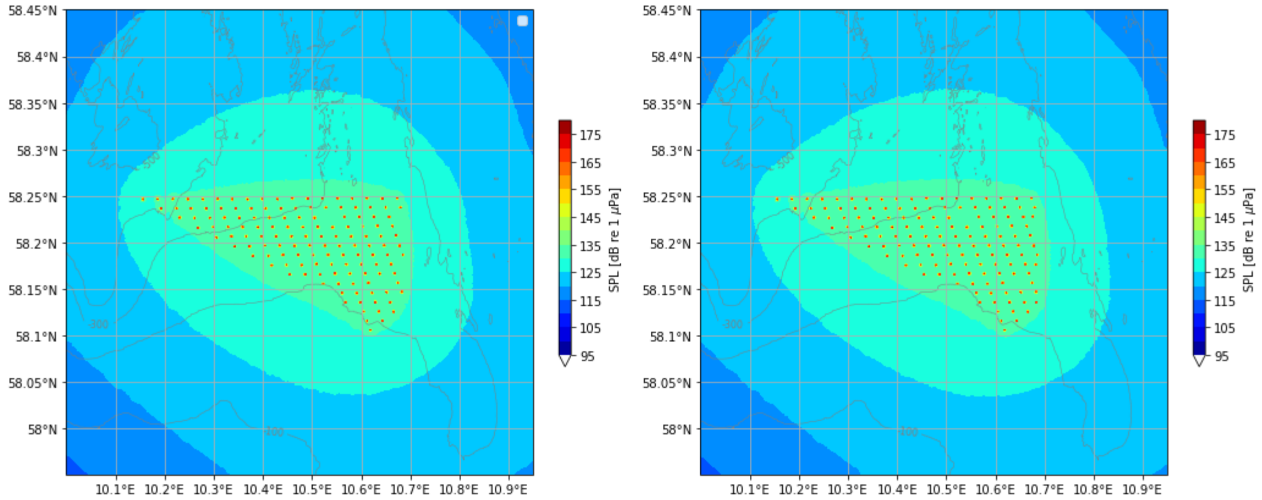

Figure 4.22 Zoomed map of the unweighted SPL at the Mareld OWF caused by the operation of the floating wind turbines (left) and the combination of the operational noise from the fish and the wind farm (right)

Only levels above the ambient noise are shown

Harbor porpoise

The modelling results show that a behavioural impact on harbour porpoises can only be expected in the direct vicinity of a single turbine or fish farm. A map of the SPL generated by the wind turbines and the fish farm in combination with the behavioural impact areas is presented in Figure 4.23 at two different spatial scales. The VHF-weighted SPL in combination with the individual TTS impact areas is shown in Figure 4.24.Figure 4.24 The comparison of the total impacted areas with and without the fish farms is presented in Table 4.10, and shows only a negligible difference for both behavioural as well as TTS impacts.

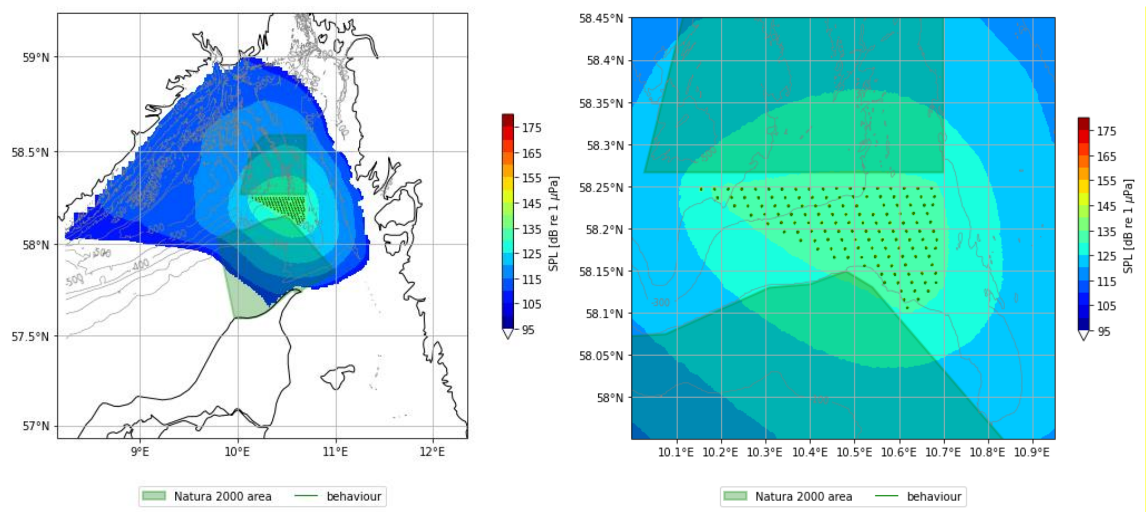

Figure 4.23 Maps of the unweighted SPL at the Mareld OWF caused by the operation of the floating wind turbines and the operational noise from the fish farm and the impact area for the behavioural response

The right plot presents a zoom into the wind farm area. Only levels above the ambient noise are shown

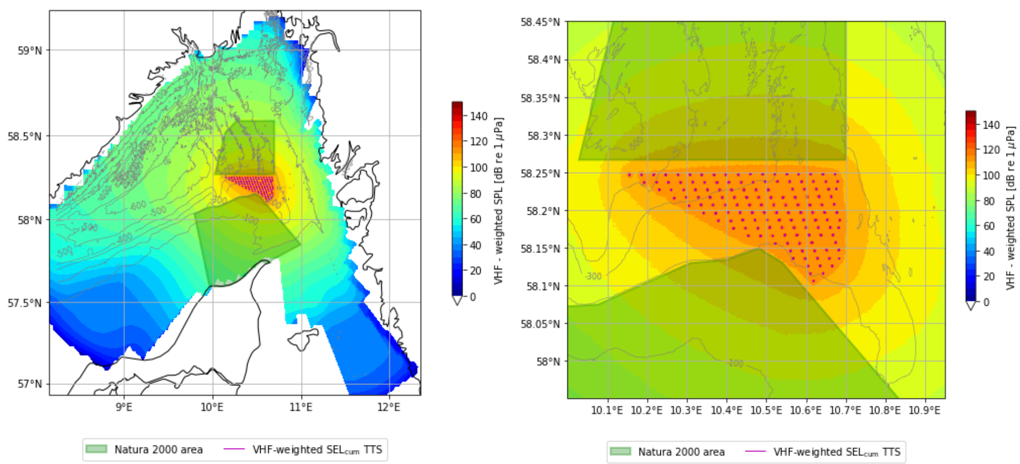

Figure 4.24 Maps of the VHF-weighted SPL at the Mareld OWF caused by the operation of the floating wind turbines and the operational noise from the fish farm and the impact area for TTS

The right plot presents a zoom into the wind farm area.

Table 4.10 The added-up impact areas and effective impact ranges of behavioural and TTS impacts for the harbour porpoise with and without the fish farm

Effect	Threshold type	Impact area turbines only [km^2]	Effective range around every turbine [m]	Impact area turbines and fish farm [km^2]	Effective range around every fish farm [m]
Behaviour	SPL	6.3	121	6.4	117
TTS	VHF-weighted SEL_{cum}	3.8	95	3.9	92

Seals

The modelling results show that TTS for seals can only be expected in the direct vicinity of a single turbine or a fish farm. A map of the PW-weighted SPL generated by the wind turbines and the fish farm in combination with the TTS impact areas is presented in Figure 4.25, at two different zoom levels. The comparison of the total impacted areas with and without the fish farm, presented in Table 4.11 showsFigure 4.24 only a negligible difference for TTS impacts.

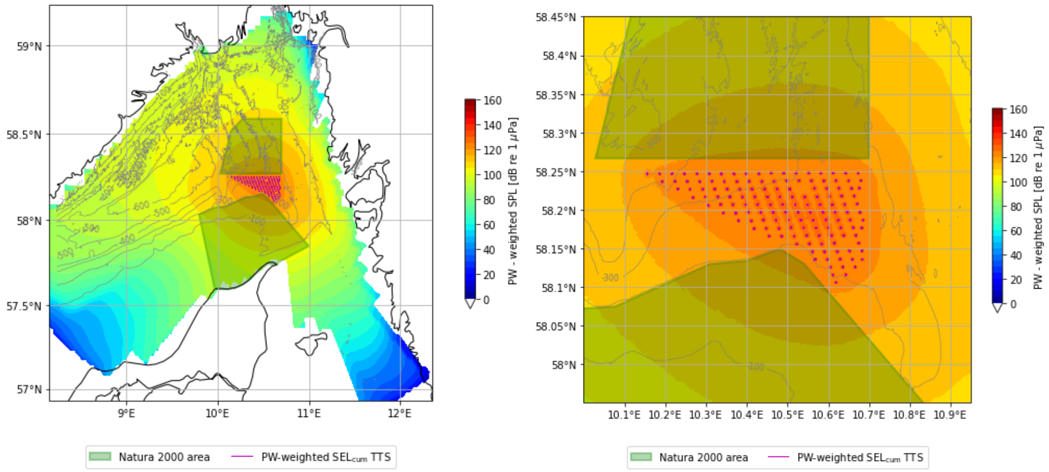

Figure 4.25 Maps of the PW-weighted SPL at the Mareld OWF caused by the operation of the floating wind turbines and the operational noise from the fish farm and the impact area for TTS

The right plot presents a zoom into the wind farm area.

Table 4.11 The added-up impact areas and effective impact ranges of TTS impacts for seals with and without the fish farm

Effect	Threshold type	Impact area turbines only [km^2]	Effective range around every turbine [m]	Impact area turbines and fish farm [km^2]	Effective range around every fish farm [m]
TTS	PW-weighted SEL_{cum}	5.1	109	5.2	117

Fishes with the swim bladder involved in hearing

The modelling results show that TTS for fishes with the swim bladder involved in hearing can only be expected in the direct vicinity of the turbine or fish farm. A map of the SPL generated by the wind turbines and the fish farm in combination with the TTS impact areas is presented in Figure 4.26, at two different zoom levels. The comparison of the total impacted areas with and without the fish farm displayed in Table 4.12, shows a negligible difference between the TTS impact areas.

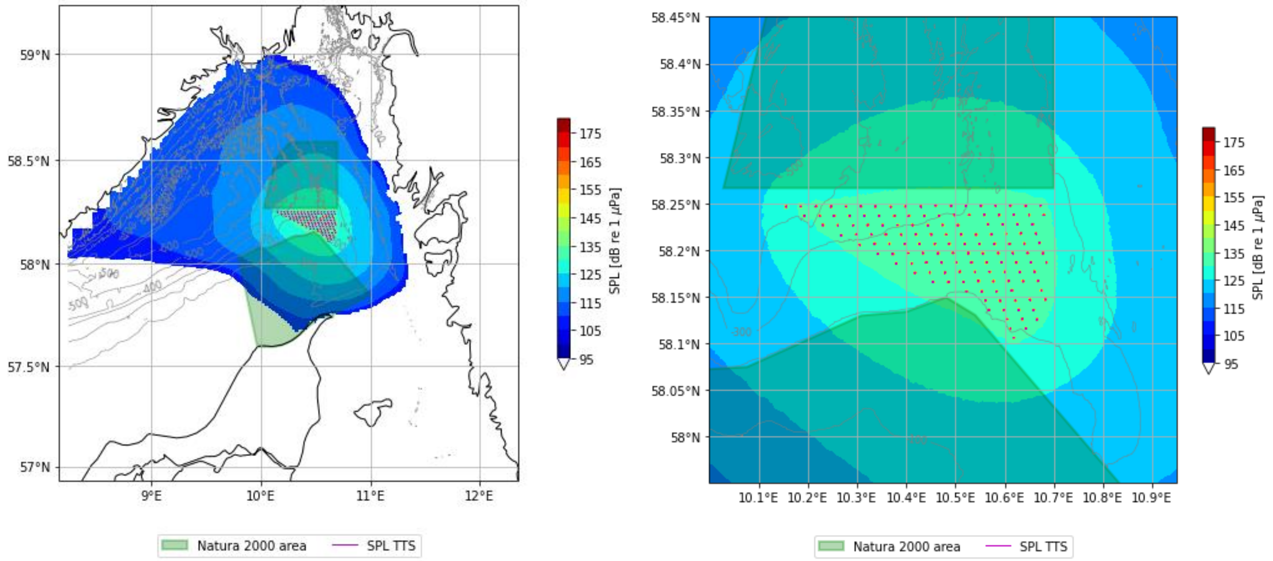

Figure 4.26 Maps of the SPL at the Mareld OWF caused by the operation of the floating wind turbines and the operational noise from the fish farm and the TTS impact areas
The right plot presents a zoom into the wind farm area. Only levels that are above the ambient are shown.

Table 4.12 The added-up impact areas and effective impact ranges of behavioural and TTS impacts for fishes with the swim bladder involved in hearing with and without the fish farm

Effect	Threshold type	Impact area turbines only [km^2]	Effective range around every turbine [m]	Impact area turbines and fish farm [km^2]	Effective range around every fish farm [m]
TTS	SPL	1.97	68	2.0	56

Farmed salmon and trout

The impact areas derived for the farmed salmon and trout are similar to the ones derived for fishes with the swim bladder involved in hearing. The modelling results show that TTS for the farmed salmon and trout can only be expected in the direct vicinity of the turbine or fish farm. A map of the SPL generated by the wind turbines and the fish farm in combination with the TTS impact areas is presented in Figure 4.27 at two different zoom levels. The total impacted area with the fish farm is displayed in Table 4.13. The effective radius around the turbines is 67 m and 56 m around the assumed source position within the fish farm. This means that the fish cages should be more than 67 m away from the turbines and the distance between the feeder platform and the cages within the fish farms should be greater than 56 m.

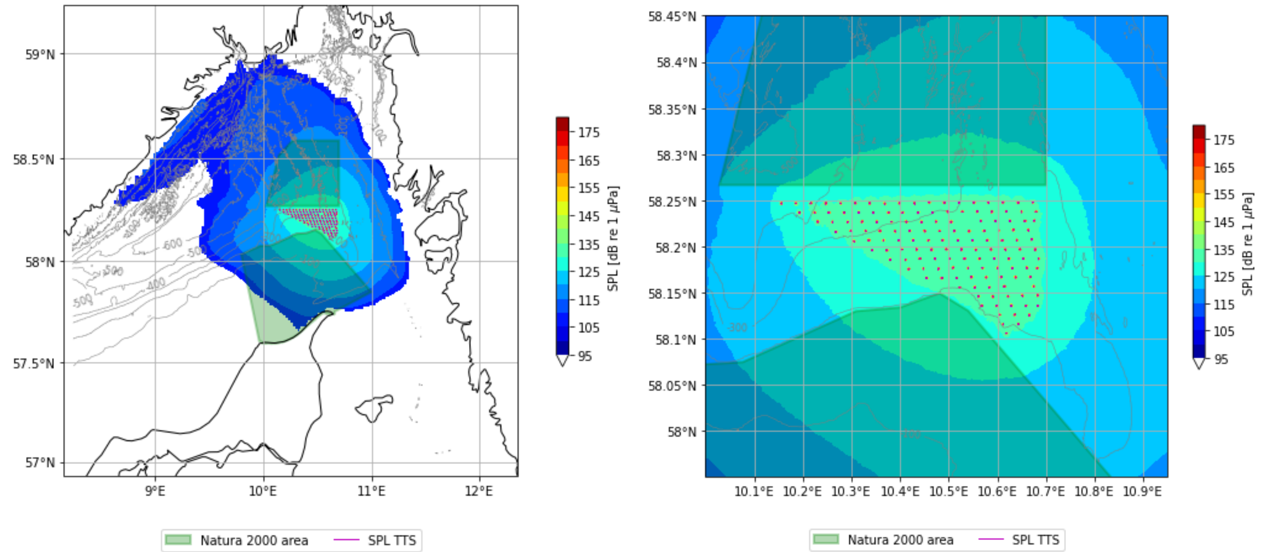

Figure 4.27 Maps of the unweighted SPL at the Mareld OWF caused by the operation of the floating wind turbines and the operation of the fish farm together with the TTS impact areas
The right plot presents a zoom into the wind farm area. Only levels above the ambient noise are shown

Table 4.13 The added-up impact areas and effective impact ranges of TTS for the farmed salmon and trout with and without the fish farm

Effect	Threshold type	Impact area turbines only [km^2]	Effective range around every turbine [m]	Impact area turbines and fish farm [km^2]	Effective range around every fish farm [m]
TTS	SPL	1.90	67	1.93	56

4.3.2 Noise from mooring lines

Measurements at three floating offshore wind farms, Hywind Norway, Hywind Scotland and Kincardine revealed transient acoustic events, raising concerns about a potential new impulsive noise source (Burns *et al.* 2022; Martin *et al.* 2011; Risch *et al.* 2023). A relatively new analysis of the most recent measurement data of Hywind Scotland conducted by Pace *et al.* (2024) found that these sounds are more continuous than impulsive in nature. Thus, Pace *et al.* (2024) suggested to treat them as continuous sound when undertaking assessment using specific noise criteria. Therefore, in this study the underwater noise caused by the mooring lines were not modelled separately. Since source level data of the Hywind Scotland wind farm are used and transient events were not excluded in the statistical evaluation of the source levels from Hywind Scotland (Burns *et al.* 2022), all different kinds of noise sources are considered within the considered source level.

The few available studies show that mooring sounds are highly variable and likely depend on the specific mooring design of each floating wind farm. Accurately characterizing the acoustic features of mooring lines would require detailed non-linear numerical modelling.

5 Influence of service vessel noise

In the following, the outcome of a literature review on the influence of service vessel noise on the considered species is provided.

The noise generated by operating vessels primarily comes from the propulsion system, with cavitation at the propeller blade tips being a major source. An additional contribution comes from water flow past the vessel, which generates broadband sound, especially at higher speeds. The levels of underwater noise depend on various factors, including the ship's type, size, hull shape, propulsion system, speed, load, and sea conditions (Smith and Rigby 2022).

The frequency and intensity of noise generated by vessels depend mainly on their size and speed. Small and fast-moving vessels create sounds that can cover frequency ranges up to 10 kHz, while large, slow-moving ships produce sounds with lower frequencies. The classification of vessels based on the frequency and intensity of generated noise, as outlined by OSPAR (2009), is presented in Table 5.1.

Table 5.1 Vessel distinction adapted from OSPAR (2009), supplemented with example vessels commonly used in offshore wind and aquaculture maintenance and their typical characteristics (typical characteristics may vary)

Vessel type	Examples	Length (m)	Sound Intensity	Sound Frequency
Small crafts and boats	Recreational craft, speed boats, operational work boats, **CTVs, AQSVs, Fish Harvesting Vessels**	<50	160-175 dB re 1µPa at 1 m.	Relatively broadband: with sound energy below 1 kHz but also ranging up to 10 kHz
Medium-sized ships	Support and research vessels, **SOVs, Fish Harvesting Vessels**	50-100	165 – 180 dB re 1µPa at 1 m.	Majority of sound energy is below 1 kHz
Large vessels	Container/cargo ships, super-tankers, cruise liners, ro-ro ships	>100	180 - > 190 dB re 1µPa at 1 m.	< 200 Hz

Service vessels are essential for maintenance access to offshore wind farms and aquaculture. The primary ships used for OWF maintenance are Service Operation Vessels (SOVs) and Crew Transfer Vessels (CTVs) (BVG 2023).

- SOVs are medium-sized vessels (60-100 m in length) that can stay offshore for weeks or even months, acting as a floating base. SOVs are typically used less frequently than CTVs but for a longer duration.
- CTVs are smaller (15-30 m in length) and can be used for daily trips to offshore sites.

In aquaculture, the most used vessels include Aquaculture Support Vessels (AQSVs) and Fish Harvesting Vessels, which are usually small or medium ships (AQUASHIP, 2025; DAMEN, 2025; Neptune, 2025; SEAPLACE, 2025).

- AQSVs ~15-50 m in length
- Fish Harvesting Vessels ~ 30-70 m in length

Based on the OSPAR (2009) classification, ships of typical SOV size primarily emit underwater acoustic energy below 1 kHz, while CTVs and AQSVs generate energy across a broader range, both below 1 kHz and up to 10 kHz. Harvesting vessels are expected to emit acoustic energy at relatively low frequencies.

On a broader scale, small and medium-sized boats contribute less to the overall low-frequency ambient noise than large commercial vessels, as they typically produce lower-intensity sounds (Table 5.1) and operate over shorter distances and durations per day. However, they can dominate the local soundscape, particularly in semi-enclosed areas where their activity is concentrated. When small vessel traffic (particularly when abundant and concentrated) overlaps with key marine animal habitats (e.g., during breeding periods), noise-related disturbances can become significant (OSPAR 2009).

Large commercial vessels are globally the dominant source of low-frequency background noise (Hildebrand 2009; McKenna *et al.* 2012) with the North Sea and adjacent waters being no exception. Since the Mareld OWF is located near high-traffic shipping lanes, the area is already subject to elevated shipping noise levels, as shown within Figure 5.1. The noise from vessels used during the operation of the combined fish and wind farm will add to these already high baseline sound pressure levels. The following qualitative assessment evaluates the potential impacts of noise from CTV's, AQSV's and SOV's and Fish Harvesting Vessels on the taxa considered in the OFFWOFF project, applying OSPAR's classification (OSPAR 2009) and documented sensitivities.

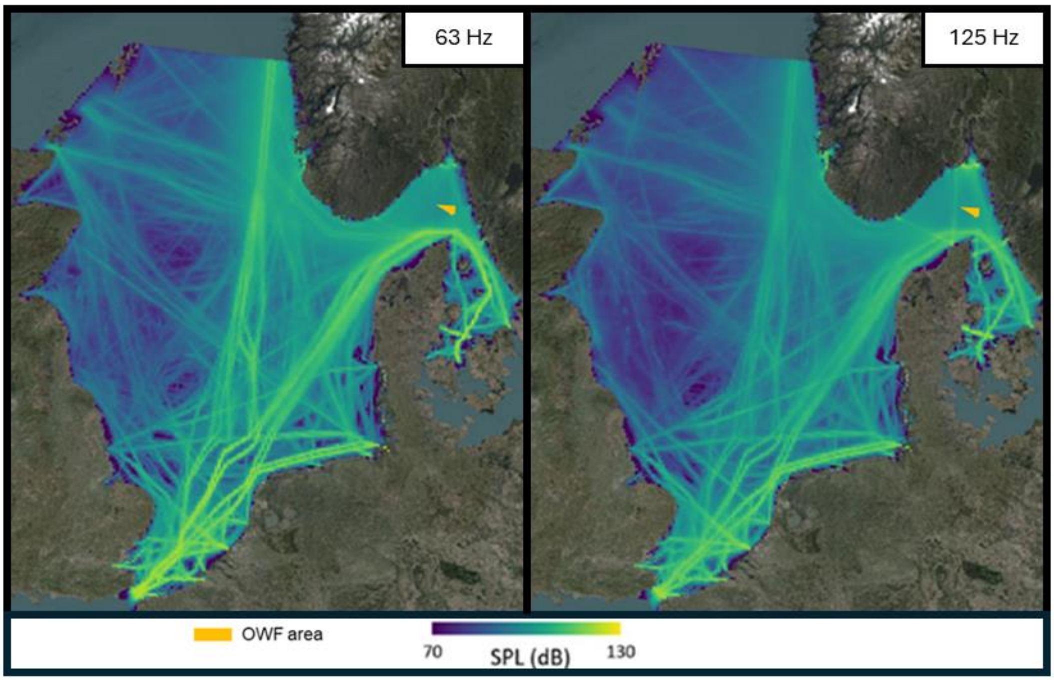

Figure 5.1 Sound levels (SPL re 1 μPa^2, in dB) of shipping noise in the North Sea for 2022 including all vessel categories at (left) 63 Hz and (right) 125 Hz.
Source: (Sertlek et al. 2024). The Mareld OWF area is highlighted

Harbour porpoise

Harbour porpoises are most sensitive to high-frequency sounds (16 to ~140 kHz) (Kastelein *et al.* 2017). The maximum sensitivity falls at ~125 kHz, which is near the peak frequency of their echolocation clicks. Harbour porpoises use echolocation for navigation and foraging (Kastelein *et al.* 2017; Miller and Wahlberg 2013).

Vessel noise and/or presence has been documented or predicted to start certain responses in harbour porpoises:

- Cessation of echolocation: High noise levels led to behavioural changes, including stopping echolocation, which significantly reduced prey capture attempts above 96 dB re 1 μPa (16 kHz 1/3 octave) (Wiśniewska *et al.* 2018).

- Potential decreased hearing and communication range/masking: the results indicated that although masking effects can occur due to the high-frequency sounds, they are short-range (60-1000 m) (Hermannsen *et al.* 2014); masking echolocation several hundred meters from a vessel (Hermannsen *et al.* 2025).
- Affected foraging (decreased surface feeding in the presence of boats (Akkaya Bas *et al.* 2017); interrupted foraging, significantly fewer prey capture attempts at received levels greater than 96 dB re 1 mPa (16 kHz 1/3 octave) (Wiśniewska *et al.* 2018).
- Behavioural effects: higher levels of porpoising as a reaction to passing vessels, suggested to be a response to high-frequency sounds (Dyndo *et al.* 2015); a more often altered behavioural state (Akkaya Bas *et al.* 2017); vigorous fluking, bottom diving (Wiśniewska *et al.* 2018).
- Affected occurrence: lower porpoise sightings in the presence of vessels (Akkaya Bas *et al.* 2017); a distribution model showed porpoise densities declining with increasing median sound levels to about 130 dB re 1μPa, but with little habitat displacement (Nehls *et al.* 2024); Porpoises avoided areas with high vessel traffic up to distances of 9 km (Pigeault *et al.* 2024).

Key findings of the literature review:

- Porpoises are sensitive to high frequencies.
- Boat noise, even though predominantly low-frequency can also include high-frequency sounds which can have a masking effect on porpoises' echolocation.
- Most studies have indicated the effects in relatively short distances and/or with high boat traffic intensities.
- Boat noise/presence can affect porpoises' behaviour and occurrence.
- Boat noise/presence can negatively affect porpoises' foraging.

Application of the literature review findings to the OFFWOFF context:

- SOVs (Service Operation Vessels), remain offshore for extended periods, primarily emit low-frequency sounds which do not affect porpoises' echolocation. While they can produce some high-frequency sound, it is generally considered to be less than that from faster, smaller Crew Transfer Vessels (CTVs). Therefore, SOVs are often assumed to pose a lower risk of echolocation masking. However, the risk of masking depends on the specific source spectra of the vessels involved. Although the spectra of large ships typically decay faster with frequency, their overall higher sound levels may still exceed those of smaller vessels at higher frequencies. Consequently, more data is needed to support definitive assessments of their relative impacts on porpoise behaviour and occurrence.
- Small and fast vessels are likely to produce high-frequency noise. However irrespective of boat size, ship traffic can affect porpoises' activity.
- That said, for OWF and aquaculture operations vessel noise levels are expected to be too low and sporadic to cause significant long-term masking and behavioural effects. While occasional short-term interference may occur, it is unlikely to substantially impact porpoises' activity.
- Moreover, the transient nature of vessel noise from OWF and aquaculture maintenance suggests that any effects would be minimal compared to those that can be caused by continuous noise from commercial shipping. However, in already noisy environments, additional emissions may still contribute to masking and other effects.

Seals

Seals are sensitive to medium-frequency sounds. Harbour seals have good hearing sensitivity between 6 and 12 kHz (Wolski *et al.* 2003).

Vessel noise and/or presence has been documented or predicted to start certain responses in harbour seals and/or grey seals:

- Potential masking and communication range reduction: A recorded ro-ro vessel sounds in the Lithuanian area of the Baltic Sea overlapped the recorded captive grey seals' communication signal throughout all frequency bands. Analysed grey seal vocalisations fell within the frequency range of 0.1–5 kHz, with central frequencies of 0.25-1.3 kHz (Bagočius 2015).
- Affecting behaviour and bottom resting: Harbour seals sonified with relatively high 2 kHz sound levels showed a higher probability of behavioural change, e.g., during a dive, seals were more likely to interrupt their bottom resting (Maurer *et al.* 2025).

Key findings of the literature review:

- Grey seal communication may potentially be masked by vessel noise due to possible frequency overlap.
- Mid-frequency noise (2 kHz) can disrupt natural behaviours, such as bottom resting during dives in harbour seals.

Application of the literature review findings to the OFFWOFF context:

- SOVs, CTVs, AQSVs and Fish harvesting vessel sounds can potentially mask grey seal communication. However, this potential effect is unlikely to occur given the low intensity of expected OWF and Aquaculture maintenance vessel traffic.
- Boats used for OWF and Aquaculture have the potential to disrupt seals behaviour, such as bottom resting (especially small crafts, which produce more noise at higher frequencies). However, given the high depth in the OWF area, this risk is likely not applicable, as seals tend to bottom rest in shallow waters. However, affecting other behavioural transitions could still be possible but not at a substantial scale, given the intensity of the OWF maintenance vessel traffic.

Fishes

Fish are most sensitive to low-frequency sounds (often <1 kHz), but their hearing is very species-specific (Popper *et al.* 2019).

Vessel noise and/or presence has been documented or predicted to start certain responses in fishes:

- Compromised antipredator behaviour: European eels exposed to ships recording sounds from ports were more likely to fall prey to predators in laboratory conditions (Purser *et al.* 2016; Simpson *et al.* 2015).
- Avoidance response: A primary literature review by Mitson (1995) concluded that ship noise can elicit avoidance reactions in fishes; a primary literature review on fish avoidance reactions to vessels by De Robertis and Handegard (2013) has shown that fish reactions to approaching vessels are variable and difficult to predict.
- Potential masking: Shipping noise has the potential to mask signals important for fish (Neenan *et al.* 2016; Radford *et al.* 2014).
- Elicitation of vigilance or anti-predator responses: Fish responded to noise from passing boats by exhibiting anti-predator behaviour (van der Knaap *et al.* 2022). As discussed in Section 3.3.2, the study, however, has methodological flaws.

Key findings of the literature review:

- Fish exposed to ship noise may be more likely to fall prey to predators.
- Fish can exhibit avoidance reactions in response to ship noise.
- Shipping noise can potentially mask signals that are important for fish.
- Fish may respond to passing boat noise by displaying anti-predator behaviour.
- Fishes' responses to noise can be variable (depending e.g. on the species)

Application of the literature review findings to the OFFWOFF context:

- Noise produced by vessels used for OWF and Aquaculture maintenance has the potential to elicit various responses in fish, such as increased vulnerability to predators, avoidance reactions, masking of important signals, and anti-predator behaviours.
- Since fish are sensitive to low-frequency sounds, larger vessels that produce most of their acoustic energy in the low-frequency spectrum could pose a greater threat, than smaller boats, especially in terms of eliciting masking effects and other behavioural changes in fish.
- Given that, typically medium-sized SOVs and medium Fish Harvesting Vessels can have the potential to affect fishes more than smaller CTVs and AQSVs.
- However, given the low intensity of service vessel traffic, it is assumed that any potential effects on fish will not be substantial, especially when compared to the impact of low-frequency emissions from heavy shipping traffic along busy routes.

Farmed salmon and trout

Atlantic salmon is less sensitive to sounds compared to many other fish species and can detect sounds below 380 Hz. It is also more sensitive to particle motion than sound pressure (Hawkins and Johnstone 1978).

There are very few studies focusing on the influence of vessel noise on salmonids. A study by van der Knaap *et al.* (2022) showed elicitation of vigilance and anti-predatory responses to boat noise. However, the study used small net pens that could have affected the fish's behaviour (more can be found in the section 3.3.2 Fishes with a swim bladder).

Other studies, however, not focused on vessel noise, showed that very low frequencies have the potential to elicit avoidance or stress effects in Atlantic Salmon (Knudsen *et al.* 1992; Oppedal *et al.* 2025). The study by Oppedal *et al.* (2025) had methodological issues, such as the lack of a control group and the use of small tanks, which may have added confounding variables and affected sound propagation. Many studies on aquaculture noise and pile driving showed no impact on salmonids (compare also section 3.3.2). As fishes that inhabit turbulent water environments, salmon and trout likely habituate to elevated sound levels. Nevertheless, a new study on behavioural and transcriptional effects of long-term noise exposure in brook trout (a freshwater trout) suggested that while fish may appear not behaviourally responsive to anthropogenic noise, they could show significant changes at the transcriptional level with possible long-term effects. This suggests that there is not only a need for more research on the influence of vessel sound on salmonids but also research that is not only focused on behavioural effects but also changes on molecular and physiological scales.

Key findings of the literature review:

- There is very limited research on vessel noise and salmonids.
- Boat noise can trigger vigilance and anti-predator responses in salmonids, though the study design may have influenced results.
- Low frequencies can cause avoidance or stress in Atlantic salmon, but the study showing a stress response had methodological flaws.
- Salmon and trout are considered not to be highly sensitive to sounds that are not of very low frequency. Studies on aquaculture and pile driving show little impact, likely due to the fish's habituation to noisy environments.
- The lack of observed behavioural effects does not necessarily mean there are no effects at smaller scales.
- More studies are needed to assess the influence of vessel noise on salmonids, particularly focusing on physiological and molecular effects to better understand the risks.

Application of the literature review findings to the OFFWOFF context:

- Given the limited research on the effects of vessel noise on salmonids, it is not possible to fully assess the risk of exposure to vessel noise for trout and salmon.
- However, given their limited responsiveness to sounds other than those of very low frequency, it can be assumed that noise generated by vessel traffic required for OWF and Aquaculture maintenance does not pose a significant risk to farmed salmon and trout.
- The lack of behavioural effects due to noise does not exclude the possibility of effects on a smaller scale (physiological, molecular), which should be further investigated.

Recommendations and Precautionary Measures

Although the impact of vessels is considered minimal, the following precautionary measures are recommended:

- Use low-noise vessels and adopt new technologies to reduce sound emissions.
- Minimize vessel speed where possible to reduce noise emissions.
- Ensure proper maintenance of vessels to prevent unnecessary increases in noise over time.

While Designated Shipping Exclusion (DSE) Zones within OWFs help reduce noise levels by preventing large ships from passing through, cumulative ship noise could become a concern in the future, given the global trend of increasing background underwater noise levels.

Identified uncertainties and data gaps

As a result of the assessment of OFFWOFF maintenance vessel noise influence on marine animals, a set of uncertainties and data gaps were identified. They are indicated in Table 5.2 including recommendations to inform better assessments in the future.

Table 5.2 Uncertainties in OFFWOFF maintenance vessel noise assessment: approaches, potential consequences, and recommendations to address the data gaps

Data gap / uncertainty	Concequence / Assumption	Recommendation to close the data gap
Publicly available measured source spectra of typical SOVs, CTVs, and AQSVs with operations within OWF are lacking	Very simplified descriptions of the noise emissions were considered.	Measurements in typical operation conditions of the different vessel types need to be published.
In some studies, it is uncertain whether porpoises or animals in general reacted to the noise generated from the vessels or just the sight of them.	For this assessment studies were incorporated, without excluding those that potentially could show reactions of animals to rather the presence of boats than the sounds produced by them.	There is a need for more studies clearly ensuring that the observed effects of vessel noise were not caused also or only by the sight of vessels.
There are not enough studies on effects of vessel noise on marine animals (especially on salmonids) to inform sufficient assessments.	Due to the very limited number of studies on salmonids, it was not possible to fully assess the risk of exposure to vessel noise for this group.	There is a need for more studies on effects of vessel noise on the marine fauna, especially for salmonids.
It is uncertain whether vessel noise would cause masking and reduce communication range in seals. However, it has been suggested that this could pose a potential risk for grey seals.	The assessment acknowledged the potential masking and reduced communication range in grey seals as a result to exposure to vessel noise.	There is a need for more studies on the potential of vessel noise to cause masking and reduced communication range in seals.

Data gap / uncertainty	Concequence / Assumption	Recommendation to close the data gap
The full range of responses to vessel noise across different fish species is not well understood, and it is assumed that these responses are species-specific.	The assessment incorporated the existing, though insufficient, data on fishes' responses to vessel noise.	There is a need for more species-specific studies on the influence of vessel noise on fish
It is uncertain whether vessel noise can elicit stress or avoidance reactions in salmonids	The assessment acknowledged the possibility that vessel noise could elicit stress or avoidance reactions in salmonids. However, due to methodological flaws in the study suggesting this effect, no threshold was derived.	There is a need for better designed studies on the stress and behavioural effects of vessel noise on salmonids.
The scarcity of data on physiological or molecular effects of underwater noise, especially in fishes (e.g. stress response)	The assessment acknowledged that the absence of observed behavioural effects of vessel noise in some fishes (e.g., salmon and trout) does not necessarily imply that no effects occur at smaller spatial scales, such as the case for physiological and molecular effects.	There is an urgent need for more studies on the effects of vessel noise on the physiology of fishes (e.g., salmon and trout) down to molecular changes.

6 Conclusions

Understanding the combined acoustic effects of offshore wind farms and fish farms is increasingly important as the marine space becomes more intensively used and multi-use platforms gain traction. This study provides a first integrated assessment of these co-located activities and their potential impacts on marine life.

Our modelling results confirm previous findings that using effective noise mitigation measures - such as a hydro sound damper, bubble curtains or other sound mitigation systems - can significantly reduce the potential impacts of pile driving on marine animals. Additionally, we show that the installation of suction anchors, whether for fish farms or floating wind turbines, is associated with minimal acoustic disturbance for both fish and marine mammals.

Importantly, our results demonstrate that the inclusion of fish farms within the Mareld OWF area does not lead to a notable increase in the overall operational noise footprint and is not expected to cause adverse effects on marine fauna and farmed salmon and trout.

Furthermore, the knowledge gaps and uncertainties associated with the acoustic aspects of the assessment and the thresholds applied in the methodology are identified. Addressing them according to the suggested recommendations could help to further increase the modelling accuracy of the different considered scenarios and increase accuracy of biological impact evaluation.

The qualitative assessment suggests that service vessel noise from OWF and fish farm operations may locally affect marine animals, though substantial impacts are unlikely due to limited traffic intensity and short ranges of influence. Precautionary measures such as reduced vessel speeds are recommended. Further research is needed to assess impacts on salmonids, focusing on physiological and molecular responses.

These findings support the feasibility of combining OWFs and fish farms in shared marine spaces, provided that appropriate mitigation measures are implemented during construction. Further research may focus on cumulative impacts over time and on site-specific species sensitivities to ensure responsible and sustainable multi-use of offshore environments.

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Appendix A Noise modelling

Appendix A.1 Source definitions

The 1/3 octave bands were used as they best represent how marine life hears. In biological hearing systems, noise is integrated over several frequency filters, called critical bands. The width of the filter is approximately 1/3 – 1/12 of an octave with Q (the bandwidth of the filter divided by the centre frequency) being relatively constant for most species. For the sake of simplicity and in accordance with other studies and noise measurements the source level are provided as 1/3 octave levels (see review by Thomsen *et al.* (2006)).

Appendix A.1.1 Pile driving

Information on the sound source

A floating foundation type is considered for the construction of the Mareld offshore wind farm. Based on the information provided by Freja Offshore, the variant consisting of an anchor pile with 2.5 m diameter was identified to be the scenario with the highest potential acoustical impact on the marine life in the area. Therefore, the assessment of the acoustical impact was conducted with this pile dimension.

The source SEL was derived by considering measurements made during the pile driving of a 2.5 m diameter pile that was used for the anchoring of a tripod foundation as reported by von Pein (2021). These measurements were scaled to the project parameters with scaling laws developed for the broadband SEL (von Pein *et al.* 2022) and for the one-third octave band spectrum of the SEL (von Pein *et al.* 2023).

The SPL and SPL_{peak} are derived by adding a constant conversion factor to the broadband SEL. The conversion factor for the computation of the SPL_{rms} was 10.5 dB, which is a frequently observed difference between SEL and SPL_{rms}. The conversion from the SEL to the SPL_{peak} was set to 23.6 dB based on a scaling procedure tailored for the respective difference (von Pein 2024).

In cooperation with the OFFWOFF project partners, the parameters were defined for the definition of the source levels for the installation of the anchor piles. These are summarized in Table A-1.

Table A-1 Parameters considered for the estimation of the source levels of the pile driving activities

Parameter	Unit	Value
Pile diameter	m	2.5
Hammer Energy	kJ	800
Ram weight	t	80
Pile length	m	45
Initial stick-up	m	40
Total number of strikes	-	7770

The cumulative SEL was calculated based on the maximum number of strikes in combination with the pile driving schedule and the decreasing SEL with increasing penetration of the installation of one pile. The estimated weighted and cumulated source levels are listed in Table A-2.

Table A-2 Source levels of the unmitigated pile driving scenario

Parameter	Unit	Value
SEL_{SRC}	dB re 1 µPa²s	216.4
$SEL_{cum,src}$	dB re 1 µPa²s	253.1
SPL	dB re 1 µPa	226.9
$SPL_{peak,src}$	dB re 1 µPa	240.0
PW weighted SEL_{src}	dB re 1 µPa²s	207.0
PW weighted SEL_{src}	dB re 1 µPa²s	243.7
VHF weighted SEL_{src}	dB re 1 µPa²s	186.1
VHF weighted $SEL_{src,cum}$	dB re 1 µPa²s	222.8
VHF weighted (Southall et al. 2019) $SPL_{125ms,src}$	dB re 1 µPa²s	190.7

A measured spectrum from von Pein (2021) is considered for the spectral decomposition of the source levels and scaled to the actual project parameters. The one-third octave band spectrum of the SEL and the considered weighted SEL are displayed in Figure A-1 together with an example of the ambient SPL.

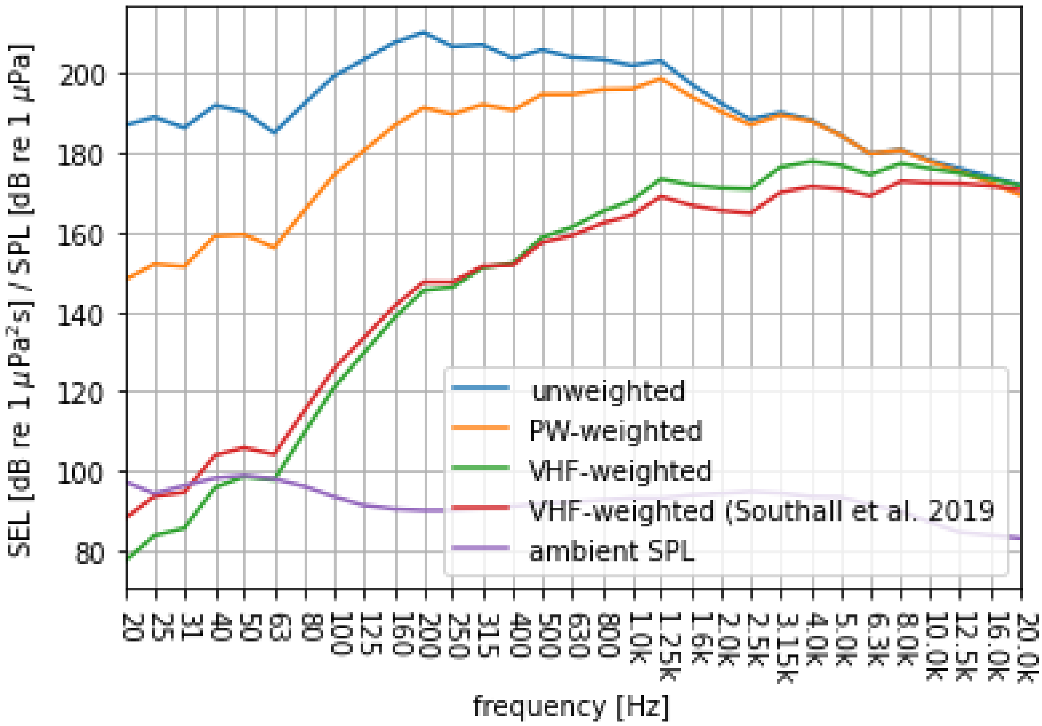

Figure A-1 The considered source spectrum of the SEL with the PW-weighted SEL, VHF-weighted SEL and the VHF-weighted SEL with the weighting functions defined by Southall *et al.* (2019)
An example of the ambient SPL is provided.

Pile driving procedure

For the modelling of the cumulative SEL three different effects were combined. According to Lippert *et al.* (2017) a reduction of the SEL of 2.5 dB per halving the pile surface sticking out of the seabed can be assumed. This reduction is combined with a driveability result, provided by Freja Offshore which indicates an increasing amount of strikes necessary to overcome the soil resistance with increasing penetration depth. This is usually expressed in number of strikes that are necessary to achieve a penetration of

0.25 m. The 2.5 dB reduction rule is combined with the driveability leading to a reduction of the SEL from the actual source level for every individual strike. Both are displayed in Figure A-2

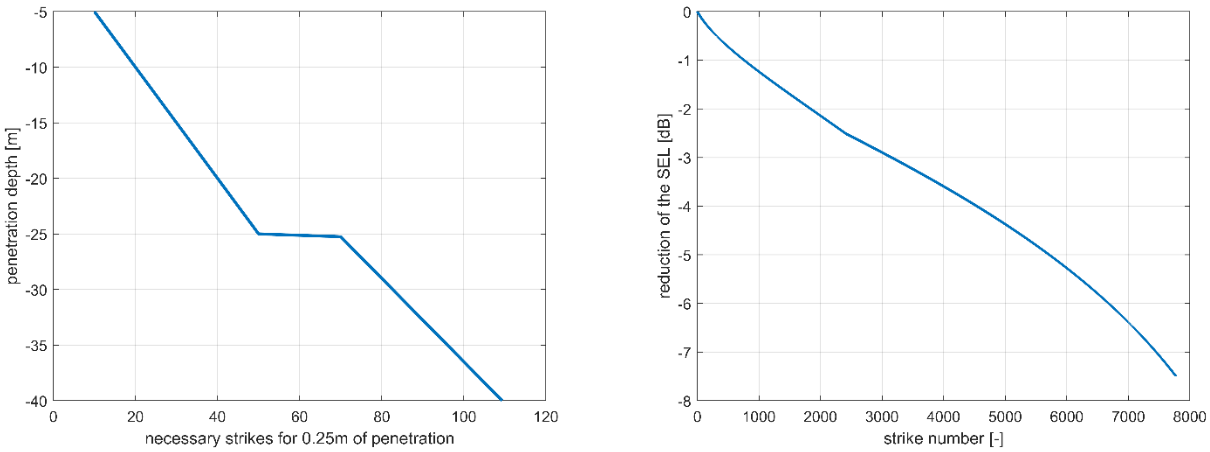

Figure A-2 Assumed driveability profile (left) and resulting reduction due to reducing stick up of the pile with increasing penetration (right)

Furthermore, the two effects are combined with a ramp-up of the strike energy. Pile driving is usually conducted with varying blow energy. The required energies are highly dependent on the soil conditions and, therefore, site-specific. The applied strike energy is usually increased with increasing penetration depth. The ramp-up procedure defined in Table A-3 was considered in the assessment of the pile driving noise.

Table A-3 Pile driving schedule applied in the modelling of the pile driving noise in the Mareld OWF

Energy level [kJ]	% of hammer max energy	Strike count [36 blows/min]
120	15	1165
440	55	1943
800	100	4662
TOTAL		7770

The strike energy *E* influence on the sound levels is scaled with:

$$\Delta \mathrm{SEL} = 10 \log_{10}\left(\frac{E_i}{E_0}\right). \qquad \text{Eq. A-1}$$

Noise abatement measures

Several different kinds of noise mitigation systems (NMS) have proven to effectively reduce the underwater noise caused by pile driving in waters with depths of up to 45 m (Bellmann *et al.* 2020; von Pein *et al.* 2024). These include systems deployed in the direct vicinity of the pile such as the Hydro Sound Damper (HSD) system or the IQIP Noise Mitigation Screen (IQIP-NMS) and bubble curtains.

Submerged pile driving at water depths considered within this project have not yet been effectively mitigated. Imaginable are systems that shield the direct path, hammer addons that reduce the emitted noise and bubble curtains, with of course different acoustical properties than currently achieved in shallow water.

Within this study, the measured insertion loss of the HSD system taken from Bellmann *et al.* (2020) is subtracted from the sound levels in the frequency domain in order to derive the impacts for a mitigated scenario. The measured insertion loss considered in this study for the mitigated scenario is displayed in Figure A-3.

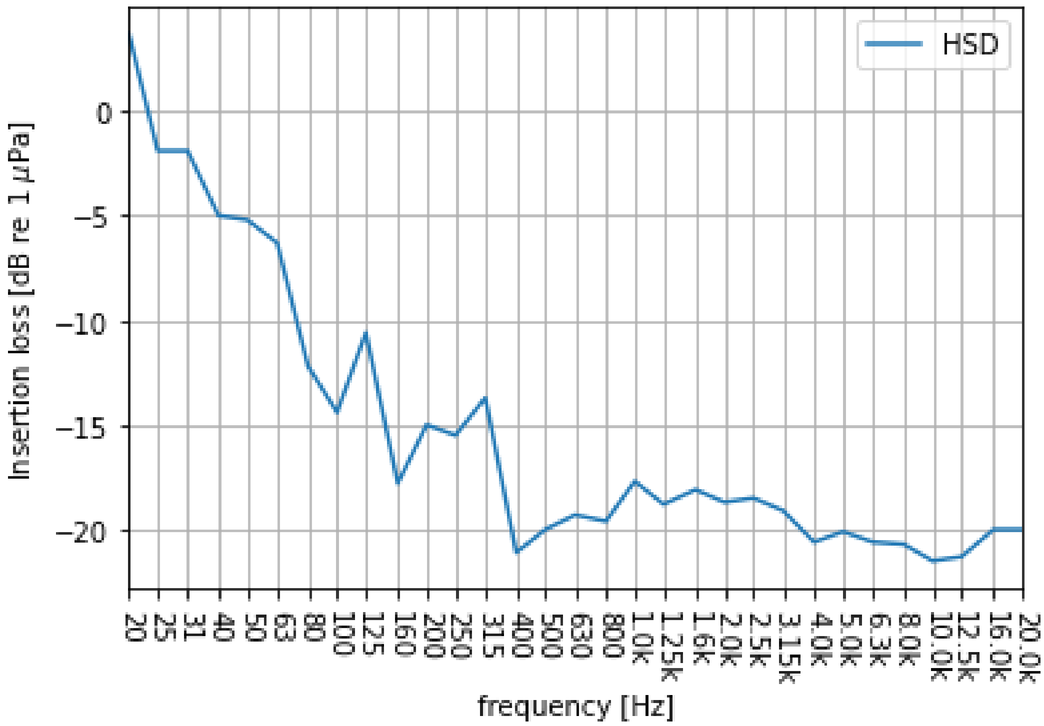

Figure A-3 Insertion loss considered for the mitigated scenario taken from Bellmann *et al.* (2020)

The considered source levels of the mitigated scenario are listed in Table A-4. Despite the provided frequency dependent insertion loss, scenarios with a broadband reduction of different SEL levels are considered in the impact assessment of the farmed fish.

Table A-4 Source levels of the mitigated pile driving scenario

Parameter	Unit	Value
SEL_{SRC}	dB re 1 µPa²s	201.5
$SEL_{cum,src}$	dB re 1 µPa²s	238.2
SPL	dB re 1 µPa	212.0
$SPL_{peak,src}$	dB re 1 µPa	225.1
PW weighted SEL_{src}	dB re 1 µPa²s	188.7
PW weighted SEL_{src}	dB re 1 µPa²s	225.4
VHF weighted SEL_{src}	dB re 1 µPa²s	166.1
VHF weighted $SEL_{src,cum}$	dB re 1 µPa²s	202.8
VHF weighted (Southall et al. 2019) $SPL_{125ms,src}$	dB re 1 µPa²s	170.6

Identified uncertainties and knowledge gaps

The parameters linked to the geometry of the pile are of course subject to optimization and may change at a later planning stage of the project. However, the actual influence on the noise levels is relatively well understood and can be adjusted with the consideration of scaling laws (von Pein *et al.* 2022).

For the assessment of hearing impairments, the SEL_{cum} is of great importance. It depends on the number of strikes, the strike energy, and the associated penetration per strike. Therefore, uncertainties that are related to the driveability analysis of the pile are directly taken forward into the assessment of acoustical impacts.

Another open question is if the 2.5 dB reduction per halving the wetted surface for the unweighted broadband SEL (Lippert *et al.* 2017) can simply be applied to the M-weighted SELs or if the decrease for the weighted SEL differs.

A very important uncertainty is the availability of noise mitigation measures and their performance in the considered depths.

Appendix A.1.2 Suction anchor installation

The noise caused by the suction anchor installation is dominated by the noise emitted from the construction vessel as shown in Remmers and Bellmann (2015). Therein measurements of suction bucket installations within the Borkum Riffgrund 1 wind farm are shown. It is furthermore shown that the pumping noise is only dominating the measured sound levels at frequencies above 1 kHz. The measurements taken at two measurement locations at a range of 500 m are considered. These are scaled to a virtual point source by adding 15 $\log_{10}(r)$ to the measured spectra. The main difference between the measurements taken at Borkum Riffgrund 1 and the Mareld site is the water depth. The water depth in the Borkum Riffgrund 1 wind farm is around 27 m. For such a shallow water location the pump and the vessel noise are emitted at a very similar position. For the deep-water scenario present at Mareld, two distinct source positions were considered. These are the pump close to the seafloor and the vessel close to the sea surface. Therefore, the measurements from Remmers and Bellmann (2015) were split into two distinct source spectra, which are shown in Figure A-4. The corresponding unweighted and weighted source levels of the two sources are provided in Table A-5.

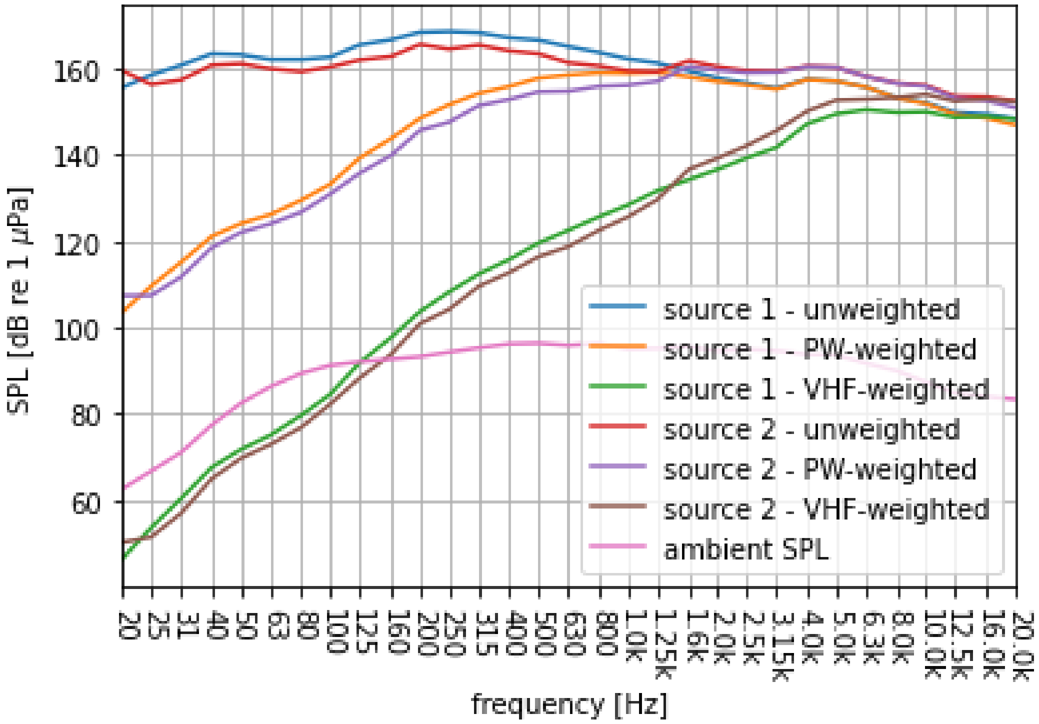

Figure A-4 The considered source spectra of the SPL with the PW-weighted SPL and the VHF-weighted SPL considered for the evaluation of suction anchor installation noise
Source 1 is referring to the vessel noise and source 2 to the noise emitted by the pump close to the sea floor. An example of the ambient SPL is provided.

Table A-5 Source levels of the two sources of the suction anchor installation scenario.

	Parameter	Unit	Value
Vessel (Source 1)	SPL_{SRC}	dB re 1 µPa	178.1
	PW weighted SPL_{src}	dB re 1 µPa	169.4
	VHF weighted SPL_{src}	dB re 1 µPa	158.5
	Cumulation time	h	24
Pump (Source 2)	SPL_{SRC}	dB re 1 µPa	175.9
	PW weighted SPL_{src}	dB re 1 µPa	170.2
	VHF weighted SPL_{src}	dB re 1 µPa	162.0
	Cumulation time	h	24

The main uncertainties in deriving the source spectra for suction anchor installation stem from the reliance on a single measurement campaign conducted in relatively shallow water. Additional uncertainties arise from the method used to separate the shallow water measurements, as well as the assumption of a 24 h cumulation period.

Appendix A.1.3 Operational noise of the turbine

At the time of publication, based on the limited data available, studies by Tougaard *et al.* (2020) and Stöber and Thomsen (2021) indicated a positive correlation between nominal power and the sound emitted by operational wind turbines. However, a subsequent study with a significantly more extensive dataset than the previous investigations (Bellmann *et al.* 2023) did not confirm this relationship, finding no evidence that sound levels increased with nominal power, see also Holme *et al.* (2023). In fact, the emitted sound from operational turbines was found to be independent of nominal power and unaffected by other factors, such as whether a gearbox or direct drive was used or the type of foundation selected (Bellmann *et al.* 2023). All of these evaluated measurements were, however, only dealing with fixed bottom turbines. Due to these latest findings, a measured spectrum deemed most representative and conservative for the investigated case was selected.

Floating offshore wind technology is not widely established yet and thus relatively little empirical data on the operational noise of floating wind turbines is available. Three recently published measurement campaigns (Burns *et al.* 2022; Pace *et al.* 2023; Risch *et al.* 2023) are particularly noteworthy. Considering the available data, a source spectrum provided by Burns *et al.* (2022) is considered for the evaluation of the operational noise. It is based on the 95th percentile source level at 25 knots wind speed and derived without the filtering of the frequently observed impulsive events. Therefore, the applied source spectrum is a conservative choice, especially in the light of 24 hours of cumulation time applied for the mammals. The spectral distribution of the source levels is shown in Figure A-5 and the respective broadband source levels are provided in Table A-6.

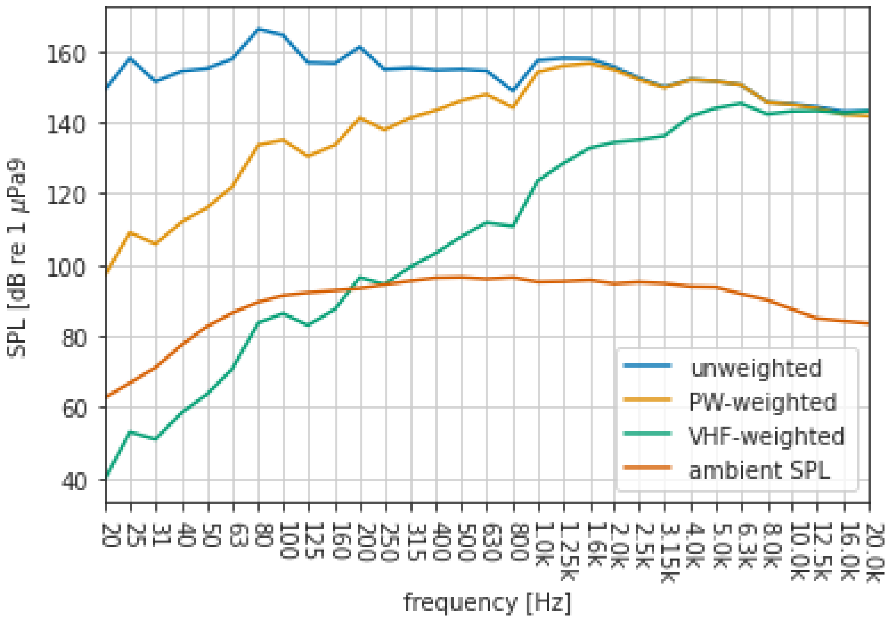

Figure A-5 The considered source spectrum of the SPL with the PW-weighted SPL and the VHF-weighted SPL considered for the evaluation of operational noise of the floating wind turbines

An example of the ambient SPL is provided.

Table A-6 Source levels of the floating wind turbines.

Parameter	Unit	Value
SPL_{SRC}	dB re 1 µPa	171.9
PW weighted SPL_{src}	dB re 1 µPa	163.7
VHF weighted SPL_{src}	dB re 1 µPa	152.6
Cumulation time	h	24

For the evaluation of the acoustical impact of the operational noise of all turbines, the noise field emitted by a single turbine derived with the propagation loss results at the dedicated source location is assumed to be emitted at every single turbine location. The total acoustical energy is cumulated to derive the noise field of the whole wind farm. The considered turbine locations are displayed in Figure A-6.

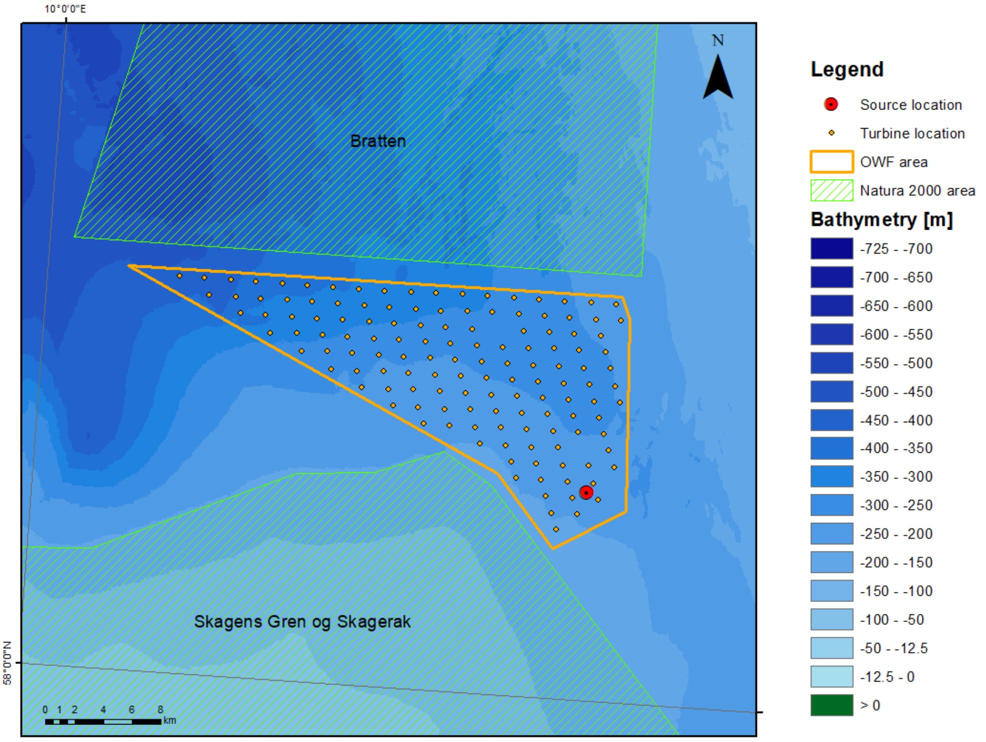

Figure A-6 Map of the turbine locations and the modelled source location within the Mareld OWF area

The primary uncertainty in deriving the source levels for operational noise lies in the comparability between the turbines, floaters, and mooring systems of the OWF where the measurements were taken and those of the Mareld OWF, as these differences may significantly influence the acoustic output. These are e.g. differences in the nominal power of 6 MW and 15 MW and could potentially be in the floater type. Additionally, using the 95th percentile of the highest measured sound pressure levels and applying this value uniformly across all turbine locations for a continuous 24 h period represents a distinctly conservative assumption.

Appendix A.1.4 Operational noise of the aquaculture

In general, there are only a few noise measurements for the operational noise of offshore aquaculture available and their focus is generally on the broadband levels. A recent review of the underwater noise at several Norwegian salmon aquacultures was conducted by Barrett and Oppedal (2025). Therein the measurement results were filtered in different frequency bands. These bands are 20-100 Hz, 100-500 Hz, and 500-1000Hz. These levels were considered within their frequency range and combined with a generic high-frequency roll-off as displayed in Figure A-7. Furthermore, an adjustment for the assumed source location was conducted.

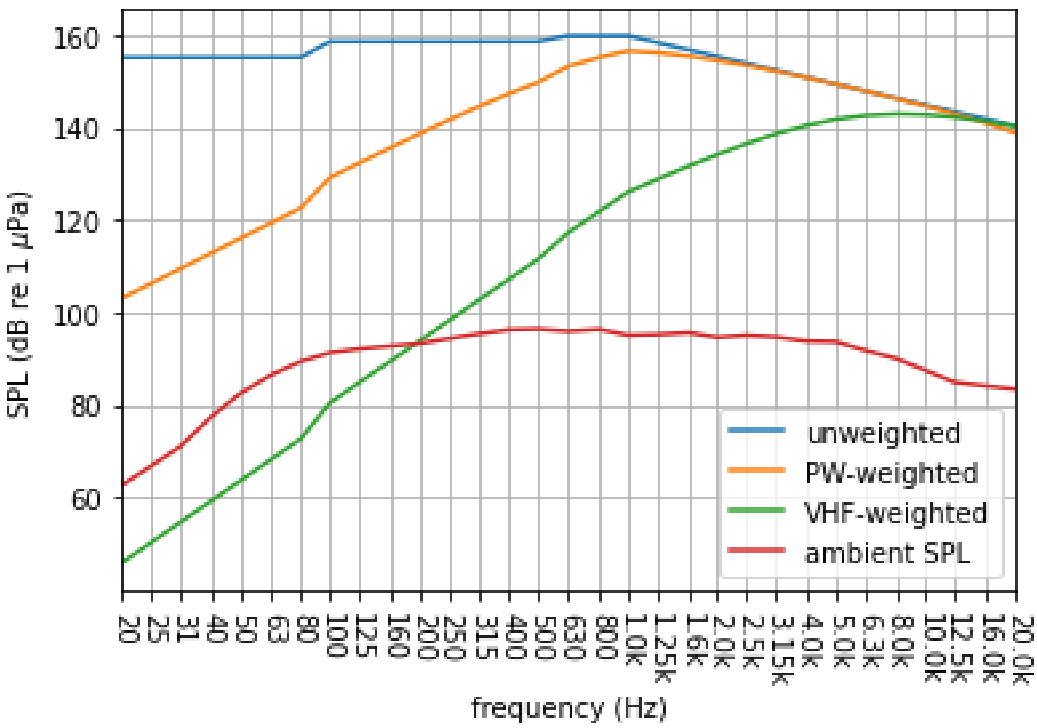

Figure A-7 The considered source spectrum of the SPL with the PW-weighted SPL and the VHF-weighted SPL considered for the evaluation of operational noise of the aquaculture
An example of the ambient SPL is provided.

The levels considered for the operational noise of the aquaculture can be regarded as a very conservative estimate. They are listed in Table A-7.

Table A-7 Source levels of the noise caused by the aquaculture.

Parameter	Unit	Value
SPL_{SRC}	dB re 1 µPa	171.2
PW weighted SPL_{src}	dB re 1 µPa	164.8
VHF weighted SPL_{src}	dB re 1 µPa	151.5
Cumulation time	h	24

For the evaluation of the acoustical impact of the operational noise of all turbines in combination with the noise emitted by the aquaculture activities, the noise field derived with the operational noise of all turbines is combined with the acoustical footprint of the three fish farms. Three locations of aquaculture are considered. Their locations are shown within Figure A-6.

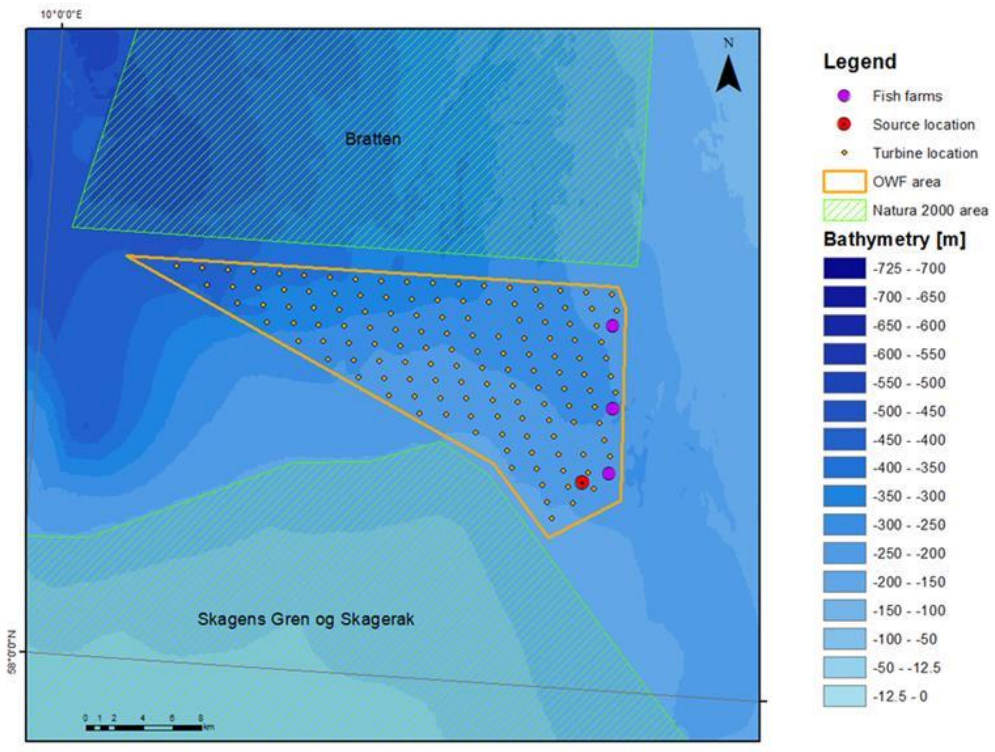

Figure A-8 Map of the turbine, fish farm locations and the modelled source location within the Mareld OWF area

The main uncertainties related to the operational noise of the fish farm are: the use of measurements originally intended to assess ambient noise levels near fish farms, rather than to determine their source levels; the unclear distance to the primary sound sources, which is based on assumptions; and the lack of detailed information on the measurement equipment and its comparability to the planned Subfarm AS facilities. For a robust acoustic impact assessment, data on the specific contributions of individual components, such as pumps, would be necessary.

Appendix A.2 Noise propagation modelling

Appendix A.2.1 Underwater acoustic simulator

The numerical noise modelling was performed using a parabolic equation and the in-house MIKE by DHI Underwater Acoustic Simulator - UAS (DHI 2023).

The model focuses on noise propagation in the far field. UAS uses the RAM code based on the sound propagation model developed by Collins (1993). A detailed description of the underwater acoustic model, including the scientific basis and the assumptions of the model, is included in the technical documentation for UAS in MIKE (DHI 2023).

- Changes in sound speed and volume attenuation in the water column.
- Sound propagation in the seabed.
- Sound spectra at 1/3 octave bands with 20 Hz to 4 kHz centre frequencies. Higher frequencies of up to 20 kHz were based on the model results at 4 kHz but corrected in accordance with frequency-dependent attenuation.

Sound propagation was calculated at discrete angular directions of the selected source location at 72 individual transects extending up to 150 km from the source. Previous investigations and literature data on the assumed sound spread from pile driving Thomsen *et al.* (2006) indicate that sound impacts are negligible after this distance. Spatial maps were then derived by integrating the results across all transects.

Simulations were carried out considering the following simplified conditions and specific assumptions:

- The sea surface is treated as a simple, horizontal, perfectly reflecting boundary ignoring the sea states, where in addition to waves, the upper ocean will have an infusion of air bubbles which has a significant impact on the speed of sound in the surface part of the water column.
- The code is a 2D model ignoring 3D effects due to the horizontal refraction of sound rays reflected by a sloped sea bottom. E.g., when the sea floor is shoaling, as is the case for the ocean over a sloping beach and the continental slope, and around seamounts and islands, a ray travelling obliquely across the slope experiences the phenomenon of horizontal refraction.
- The transmission loss of point source locations at 215 m and 30 m below the sea surface were computed.
- Near-field effects are neglected in the present study, which is judged to have a minor effect on the far-field sound pressure level. At impact ranges of interest (e.g., > 100 m), the sound intensity effects and oblique radiated sound waves dominating the near field are diluted significantly.

Other assumptions and simplifications regarding the input data and impact assessment are described in the subsequent sections.

Sound source properties were fed into the propagation model to calculate the sound propagation in angular directions from the location of piling at 72 transects in 2D. Specific 1/3 octave bands with centre frequencies from 20 Hz to 4 kHz were modelled. For higher frequencies, the propagation losses at 4 kHz were applied in combination with a correction for the increasing volume attenuation with increasing frequency (Francois and Garrison 1982a, b). Based on the numerical model results, maps were developed presenting the sound exposure level as the function of distance from the sound source.

Uncertainties in the propagation modelling arise from possible deviations in the considered water parameters, such as temperature, pH, salinity, as well as the considered soil profile. This is particularly relevant since only one geoacoustic profile and one sound speed profile within the water column are used for the entire area. Therefore, great care was taken in selecting these profiles to ensure that the parameters are representative of the whole study area. Furthermore, the modelling assumptions stated above such as treating the sea surface as a flat boundary can lead to differences between modelling results and real-life measurements.

Appendix A.2.2 Sound speed profile

Sound propagation in seawater is influenced by several factors, including temperature, pressure, salinity, density and, to a lesser extent, acidity (pH value). Therefore, information on those properties is important for the model setup.

Data for pH was obtained from the World Ocean Database (WOD). The World Ocean Atlas (WOA) 2023 was selected for the analysis of temperature (Locarnini *et al.* 2023) and salinity (Reagan *et al.* 2023). The temperature and salinity data were converted into a sound velocity profile with the use of the UNESCO equation (Unesco 1983).

Porpoises breed in the summer season in that area, therefore underwater noise propagation modelling was performed for a summer period (June, July, August), as it was considered the worst-case scenario in relation to harbour porpoises.

Vertical profiles of water characteristics and the sound speed profile used in the model setup are shown in Figure A-9 and Figure A-10 respectively.

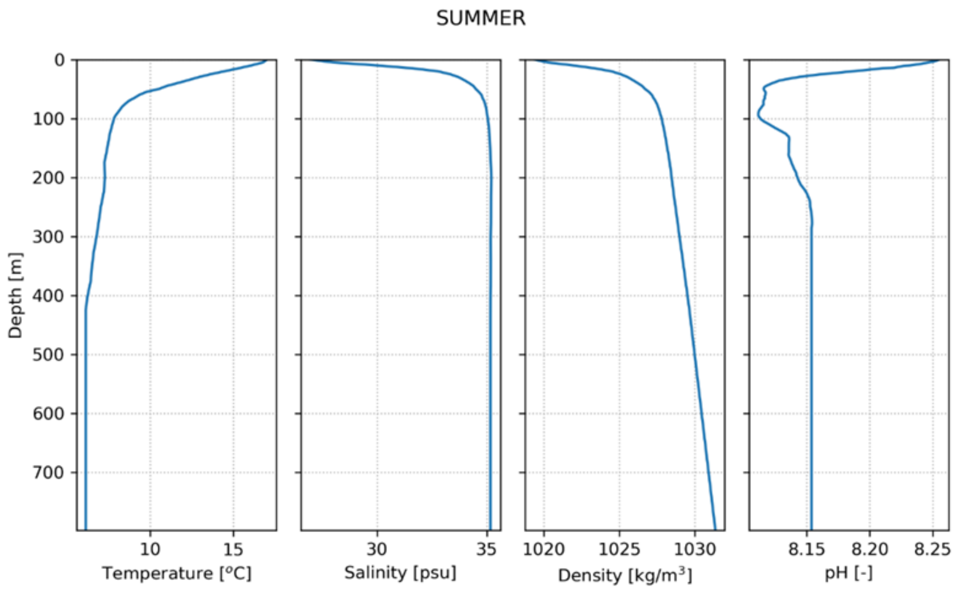

Figure A-9 Vertical Profiles of Temperature, Salinity, Density, and pH considered in the underwater noise modelling

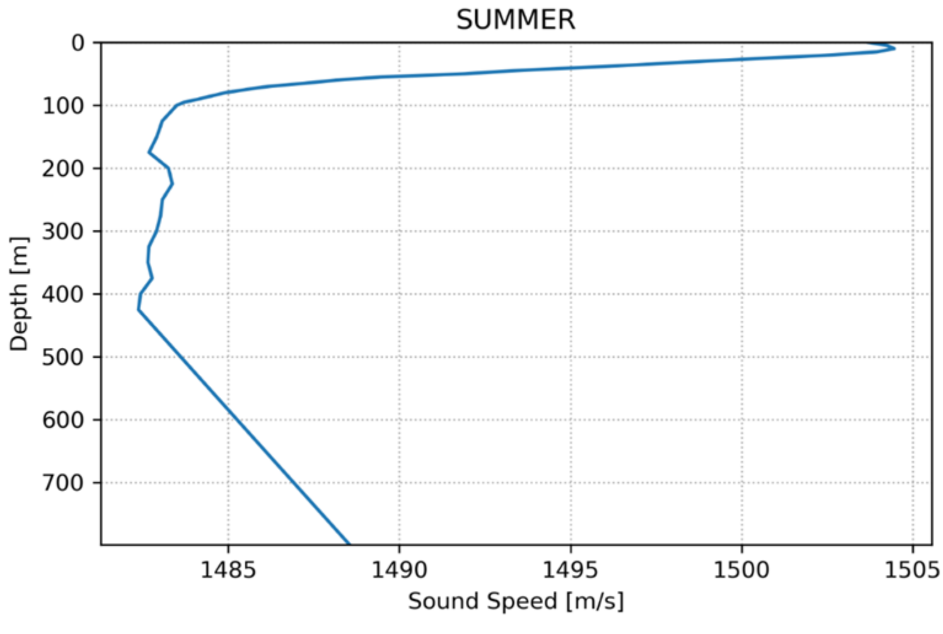

Figure A-10 Vertical Sound Speed Profile considered in the underwater noise modelling

Appendix A.2.3 Geo-acoustic profile

The seabed profile for choosing the location for underwater noise modelling at the Mareld OWF site was derived from Fugro (FUGRO 2022) and the SGU national study (Nyberg 2022). Geo-acoustic properties were estimated based on standard literature values (Jensen *et al.* 2011) and the experience from other projects. The summary of the seabed profile and geo-acoustic properties of the layers for Mareld is presented in Figure A-11.

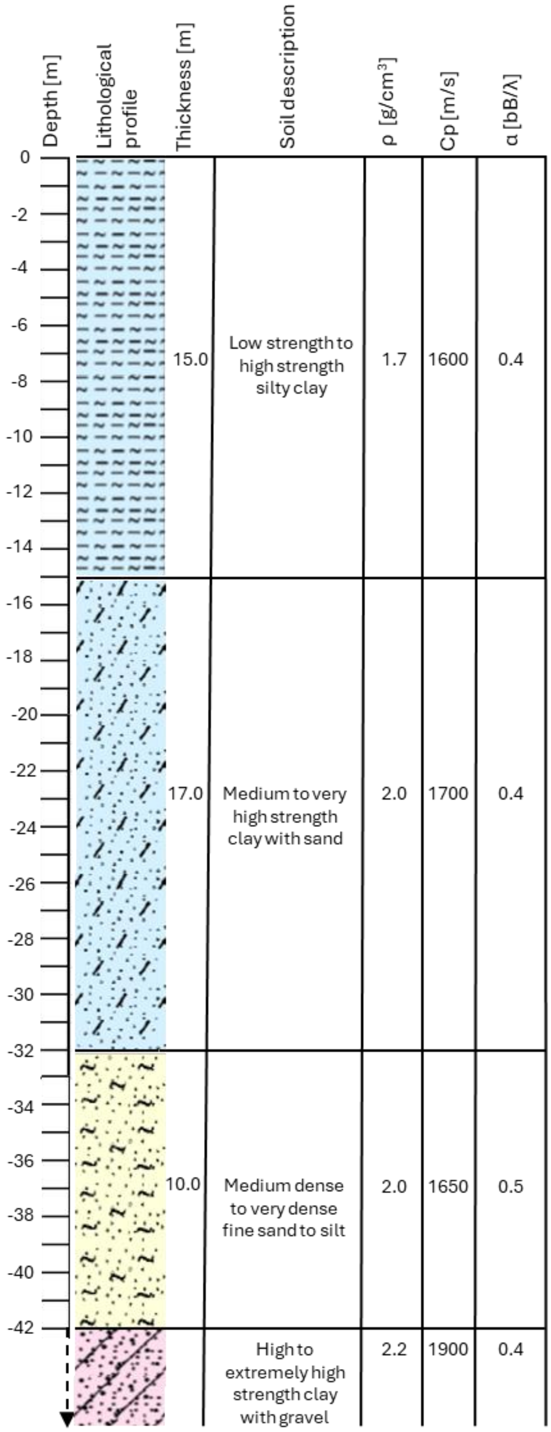

Figure A-11 The considered geo-acoustic profile for the Mareld OWF

Appendix B Identified knowledge gaps on biological effects in relation to the study

During the study, several knowledge gaps and uncertainties were identified regarding the biological effects and impacts of noise from the planned floating wind farm on fish held in aquaculture at the same location. These are summarized in Table B-1, which outlines each identified gap or uncertainty, the approach taken in this study to address it, the potential consequences, and recommendations for closing the gap.

Table B-1 Overview of the knowledge gaps identified in the study

Uncertainty/knowledge gap	Chosen approach and possible consequence	Recommendation to close the data gap
No established behavioural or stress thresholds for farmed salmon and trout exposed to pile-driving noise.	No behavioural criterion was applied for modelling pile-driving noise. This may result in an incomplete assessment, although available studies suggest limited behavioural effects on salmonids.	Conduct targeted studies on behavioural, physiological, and molecular responses of salmonids to impulsive noise.
Same TTS and recoverable injury thresholds applied to species with different hearing capabilities.	Thresholds from Popper et al. (2014) were applied uniformly to species with and without swim bladders involved in hearing. This may overestimate impacts for species with less sensitive hearing.	Revise injury thresholds based on updated, species-specific data differentiating hearing capabilities.
Lack of behavioural and stress criteria for continuous noise in fish, including farmed salmon and trout.	No behavioural or stress thresholds were applied for continuous noise, possibly leading to an incomplete risk evaluation.	Promote research into behavioural and stress responses to continuous noise, particularly in salmonids, with data quality sufficient to support threshold development.
Experimental studies lack ecological realism (e.g., small tanks, no control groups).	Most available studies cannot be used to establish criteria due to artificial settings or flawed methodologies. This undermines ecological relevance.	Future studies should use field-based or semi-natural conditions, with proper controls and baseline assessments.
No continuous noise criteria for TTS and recoverable injury in species without swim bladders involved in hearing (e.g., salmonids).	Thresholds for species with swim bladders involved in hearing were used as precautionary proxies, which may overestimate impacts in less sensitive species.	Conduct targeted studies on fish with a swim bladder that is not involved in hearing, including salmon and trout, to derive appropriate thresholds.
Existing TTS and injury thresholds for continuous noise are based on goldfish, which have atypically sensitive hearing.	Using goldfish-based thresholds introduces potential overestimation of effects in most marine fish species.	Update criteria as new, species-specific data become available.
Thresholds used in modelling assume prolonged exposure	Fish movement was not accounted for in the modelling,	Encourage research and modelling approaches that

Uncertainty/knowledge gap	Chosen approach and possible consequence	Recommendation to close the data gap
durations (e.g., 12 h for TTS, 48 h for injury), ignoring fish mobility.	potentially exaggerating exposure duration and impact range.	integrate fish movement to better reflect real exposure scenarios.
No behavioural response threshold for seals exposed to operational noise.	Behavioural impacts on seals were not modelled, potentially omitting an important impact pathway.	Conduct focused studies on seal responses to operational noise to enable future inclusion in assessments.

Appendix C Additional acoustical results

Appendix C.1 Pile driving

Appendix C.1.1 Unmitigated pile driving

Within Figure C-1 the SEL over depth and range are shown for the unmitigated pile driving noise scenario. The location and numbering of the transects are also defined Figure 4.2. The influence of the bathymetry on the sound propagation can be observed.

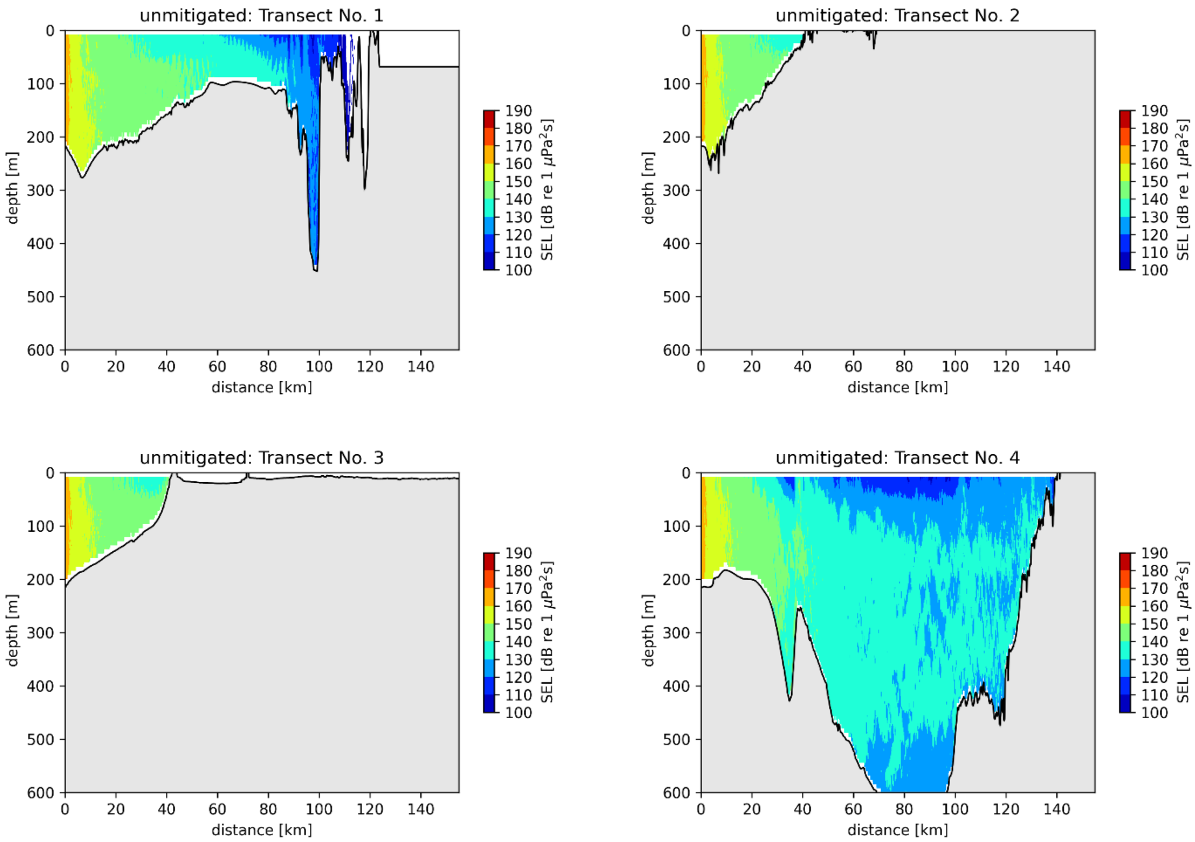

Figure C-1 The unweighted SEL over depth and range for the four transect cuts shown in Figure 4.2 resulting from the unmitigated pile driving in the Mareld OWF
Only levels above the ambient noise are shown**.**

Appendix C.1.2 Mitigated pile driving

The SEL over depth and range for the four transects is shown for the mitigated pile driving noise scenario in Figure C-2. The influence of the bathymetry on the sound propagation can be observed. The location and numbering of the transects are also defined Figure 4.9.

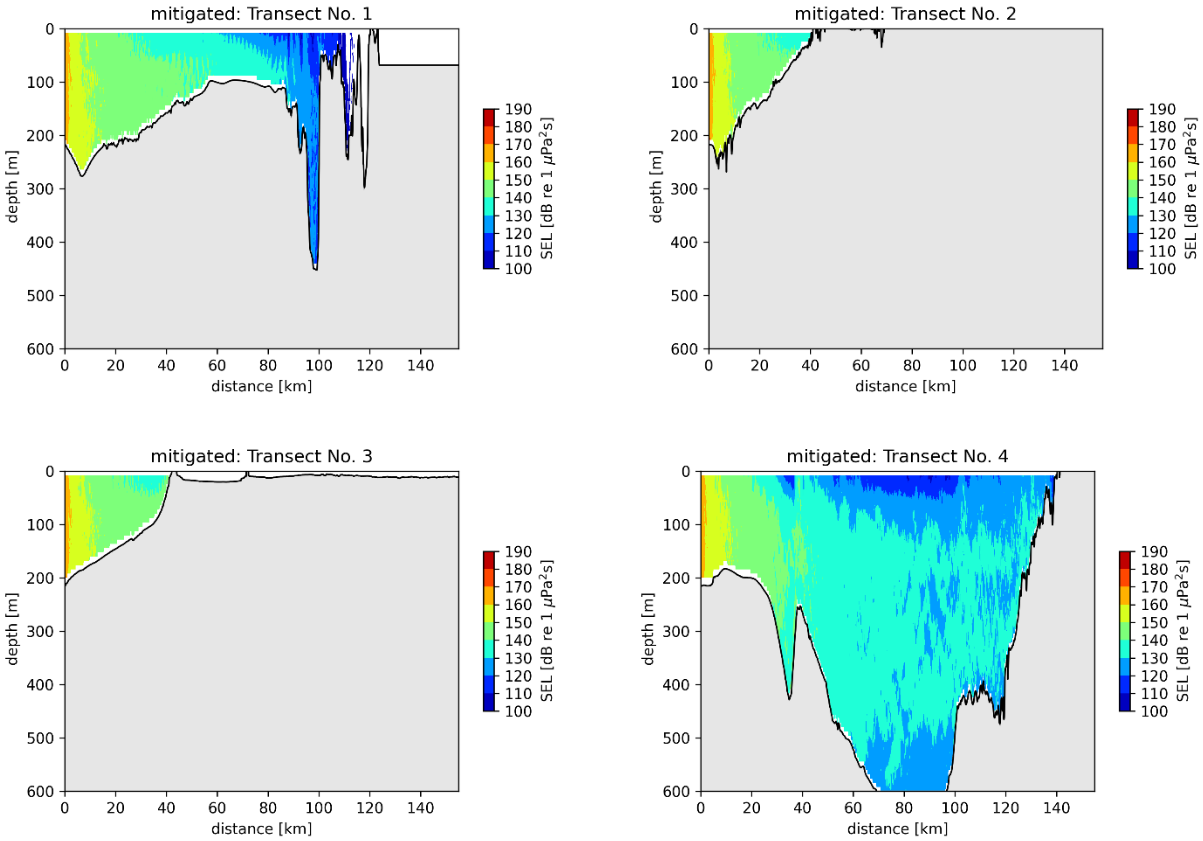

Figure C-2 The unweighted SEL over depth and range for the four transect cuts shown in Figure 4.9 resulting from the mitigated pile driving in the Mareld OWF

Only levels above the ambient noise are shown**.**

Appendix C.2 Suction anchor installation

The effect of bathymetry on the sound propagation from suction anchor installation is shown in Figure C-3. The sound levels are presented as SPL across depth and range for the four transect cuts shown in Figure 4.16.

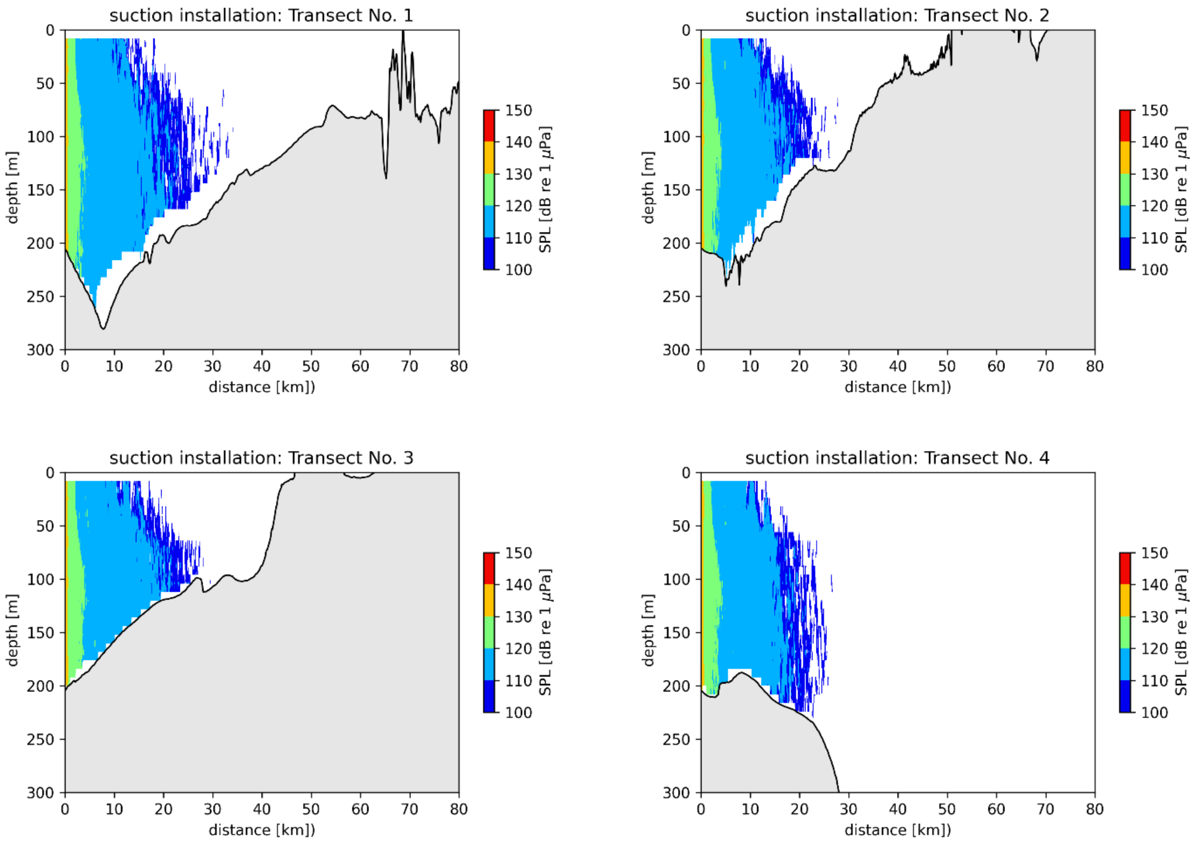

Figure C-3 The unweighted SPL over depth and range for the four transect cuts shown in Figure 4.16 resulting from the suction anchor installation work in the Mareld OWF
Only levels above the ambient noise are shown.

Appendix D Acoustical Terminology

The underwater acoustic signal produced by an acoustical source is propagating to the receiver (e.g. marine mammals and fish) and is thereby attenuated because of geometric spreading, sound absorption, scattering, reflection, and refraction. All of these propagation effects are highly frequency dependent with different mechanisms dominating different frequency ranges. Therefore, the propagation effects are site-specific, which is accounted for with the considered environmental parameters in the noise propagation modelling.

A very important differentiation in acoustics is the impulsiveness of the emitted noise. Therefore, different thresholds have been developed for impulsive and continuous noise. Typical examples for impulsive noise are pile driving or noise from the application of explosives. Vessel or operational noise are usually referred to as continuous.

In the following the acoustical terminology used in this study is described.

Appendix D.1 Sound levels of impulsive noise

Impulsive sound in the time domain is usually defined by a sharp increase in the acoustical pressure and a decay afterwards. A typical pile driving noise signal of unmitigated pile driving is displayed in Figure D-1. Therein, the part of the acoustical signal dominating the sound exposure level (SEL) is highlighted in red. The SEL is a measure for the acoustical energy of the signal. The SEL can be combined with the time duration of the red signal to derive the root mean squared sound pressure level often referred to as SPL_{rms}, SPL rms and in this report as SPL. The absolute maximum amplitude of the time signal defines the peak sound pressure level SPL_{peak}. The distribution of the acoustical energy can also be evaluated in one-third octave bands which is shown in the right plot. This allows the application of weighting functions and the combination with the frequency dependent propagation effects. Adding up the weighted and propagated SEL of all bands leads to the received SEL.

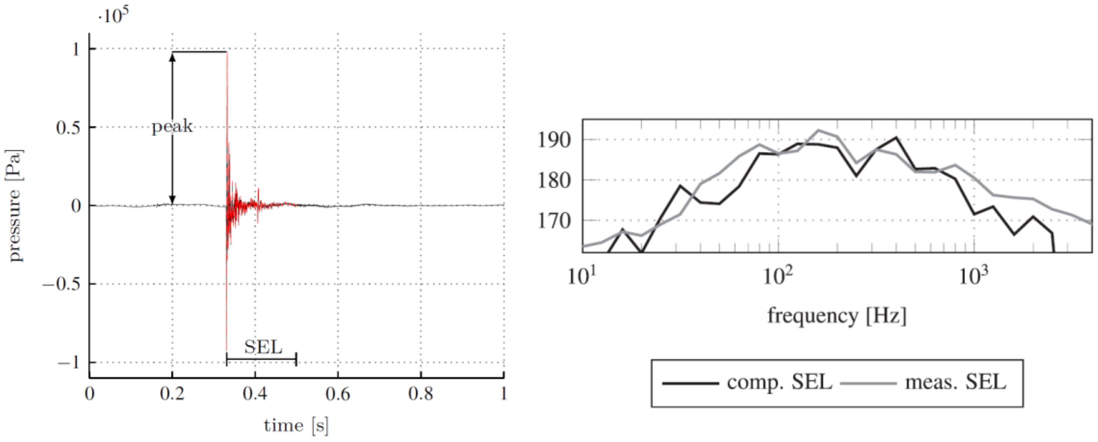

Figure D-1 Examples of the time domain pressure signal of a pile driving event (left side) and a representation of the SEL in the one-third octave band spectrum

The SEL is defined with the sound exposure Ep, and the reference value E_{p0}=1 µPa^2 s over the whole duration of the impulsive event by:

$$\mathrm{SEL} = 10\log_{10}\left(\frac{E_p}{E_{p0}}\right) = 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} \frac{p^2(t)}{E_{p0}}\mathrm{d}t\right) \quad \text{with} \quad E_{p0} = 1\ \mu\mathrm{Pa}^2\mathrm{s} \qquad \textbf{Eq. D-1}$$

The SPL also considers the time duration $T_0 = t_{\mathrm{start}} - t_{end}$ of the signal duration by:

$$\mathrm{SPL_{rms}} = 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} \frac{p^2(t)}{T_0 p_0}\mathrm{d}t\right) \quad \text{with} \quad p_0 = 1\ \mu\mathrm{Pa} \qquad \textbf{Eq. D-2}$$

A special case is the SPL with a pre-defined time such as the SPL_{125ms} which is derived with T_0=0.125 s.

The weighted SEL and SPL are derived by adding the weighting function *W(f)* to the spectral representation of the SEL by

$$\mathrm{SEL_{weighted}} = 10\log_{10}\left(\sum_f 10^{0.1\,\mathrm{SEL}(f) + 0.1\,W(f)}\right) \qquad \textbf{Eq. D-3}$$

and the SPL

$$\mathrm{SPL_{weighted}} = 10\log_{10}\left(\sum_f 10^{0.1\,\mathrm{SPL}\,(f) + 0.1\,W(f)}\right) \qquad \textbf{Eq. D-4}$$

The transmission loss is a measure of the accumulated decrease in acoustic intensity as the sound pressure wave propagates outwards from a source, hence the loss during the transmission from the source to the receiver. The influence of the sound propagation is usually described in terms of the transmission loss (TL) per 1/3 octave frequency band TL(f) with the frequency *f* and the pressure amplitude *p* the transmission loss is defined as

$$\mathrm{TL(f)} = -10\log_{10}\left(\frac{p^2_{\mathrm{received}}}{p^2_{\mathrm{source}}}\right) \qquad \textbf{Eq. D-5}$$

Since both the source (SRC) sound levels and the transmission loss are frequency dependent, the total level is computed per 1/3 octave band. The range and depth dependent total sound exposure level is defined with the transmission loss and the weighting function *W(f)* defined in Appendix D.3 by:

$$\mathrm{SEL} = 10\log_{10}\left(\sum_f 10^{0.1\,\mathrm{SEL(f)}^{\mathrm{SRC}} - 0.1\,\mathrm{TL(f)} + 0.1\,W(f)}\right) \qquad \textbf{Eq. D-6}$$

In case of the unweighted SEL, *W(f)* is equal to zero.

Exposure criteria require considering the strength of the impulsive noise and to evaluate the biological impact of a noise dose. The cumulative sound exposure level is the best analytical description of the acoustic dose from an activity because it covers the entire acoustic energy emitted. In principle, the acoustic events (e.g. construction noise) are added to one another to arrive at this dose. The term cumulative sound exposure level ($\mathrm{SEL_{cum}}$) is used in underwater acoustics (Gill *et al.* 2012). It should not be confused with cumulative impacts usually used when impacts from several different locations (for example different projects) are analysed. If all the impulsive noise events (such as hammer strikes) are equal, the cumulative sound exposure levels are described by:

$$\mathrm{SEL_{cum}} = \mathrm{SEL} + 10\log_{10}(n) \qquad \textbf{Eq. D-7}$$

where the SEL of a single impulsive event is combined with is the number of impulsive noise events *n* (e.g. number of strikes). If the events vary in strength *n* is equal to the sum of the ratio of the acoustical energy of the SEL of a single impulsive event to the ones that are cumulated.

For moving receivers, the sound exposure levels are cumulated along the escape routes, e.g. along a straight line away from the sound source,

$$\mathrm{SEL}_c^{\mathrm{moving}} = 10\log\sum_{i=1}^{N} 10^{\frac{(\mathrm{SEL}-\mathrm{TL}(r_0+vt_i))}{10}} \qquad \textbf{Eq. D-8}$$

where the calculation involves *N* impulsive sound events the SEL of a single impulsive event (such as a single hammer strike) after applying the frequency weighting, which is lined out in Appendix D.3. The transmission loss TL can be obtained from the numerical simulations at distance $r = r_0 + vt_i$ with initial distance of r_0, escape speed v and t_i the time since the beginning of the impulsive noise operations.

The $\mathrm{SPL_{peak}}$ is defined with the maximum amplitude of the time domain signal *p(t)* as defined in Figure D-1.

$$\mathrm{SPL_{peak}} = 10\log_{10}\left(\frac{\max\left(p^2(t)\right)}{p_0^2}\right) \text{ with } p_0 = 1\ \mu\mathrm{Pa} \qquad \textbf{Eq. D-9}$$

The applied modelling framework assumes a constant difference between the $\mathrm{SPL_{peak}}$ and the SEL. With the conversion factor $\Delta_{\mathrm{SPLpeak\text{-}SEL}}$ the $\mathrm{SPL_{peak}}$ is derived by

$$\mathrm{SPL_{peak}} = \mathrm{SEL} + \Delta_{\mathrm{SPL_{peak}}-\mathrm{SEL}} \qquad \textbf{Eq. D-10}$$

which neglects the additional dispersion of the pulse in the time domain and thus leads to a conservative estimate of the $\mathrm{SPL_{peak}}$ at the receiver location. The same assumptions apply for the estimation of the SPL with a different conversion factor $\Delta_{\mathrm{SPL\text{-}SEL}}$

$$\mathrm{SPL} = \mathrm{SEL} + \Delta_{\mathrm{SPL}-\mathrm{SEL}} \qquad \textbf{Eq. D-11}$$

Appendix D.2 Sound levels of continuous noise

Continuous noise is generally described with the SPL. An important aspect in the evaluation of the SPL is the considered time window T_0. Usually, statistical evaluations of the measured SPL with the consideration of 1 s windows are provided in e.g. ambient noise studies. Within this study the maximum SPL is considered for the behavioural reaction of mammals and for the hearing impairment of fish.

$$\mathrm{SPL} = 10\log_{10}\left(\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} \frac{p^2(t)}{T_0 E_{p0}}\mathrm{d}t\right) \text{ with } p_0 = 1\ \mu\mathrm{Pa} \qquad \textbf{Eq. D-12}$$

The cumulated sound exposure level once again represents the total acoustical dose received by the receiver. The measure for the total acoustical dose is the SEL_{cum}. The SEL_{cum} is derived by cumulating the acoustic energy of the 1 s time window (SPL) over the time period (T_{cont} in seconds) the continuous noise is expected to last.

$$\mathrm{SEL_{cum}} = \mathrm{SPL} + 10\log_{10}(T_{\mathrm{cont}}) \quad \textbf{Eq. D-13}$$

The respective differences between the SPL and the SEL_{cum} are 49.4 dB for an exposure time of 24 hours, 46.4 dB for 12 hours, and 43.4 dB for 6 hours.

Appendix D.3 Weighting

Marine mammals are divided into functional hearing groups based on the way, in which they perceive sound. Different hearing characteristics related to the range of sounds, a particular group of animals perceives, were compared by the National Marine Fisheries Service (NMFS 2024; Southall *et al.* 2019) with the use of frequency weighting expressed as:

$$W(f) = C + 10\log_{10}\left(\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right) \quad \textbf{Eq. D-14}$$

where the parameters *a, b* and *C* and the frequencies f_1 and f_2 of the species of interest within this project are presented in Table D-1. The corresponding weighting curves are presented in Figure D-2. The hearing ranges are presented in Table D-1.

Table D-1 Functional hearing groups with the estimated audible frequency ranges (NMFS 2024; Southall *et al.* 2019)

Functional Hearing Groups	Estimated hearing range	a	b	f_1 [kHz]	f_2 [kHz]	C [dB]
Very high-frequency (VHF) cetaceans (Southall *et al.* 2019)	200 Hz – 165 kHz	1.8	2	12	140	1.36
Very high-frequency (VHF) cetaceans (NMFS, 2024)	200 Hz – 165 kHz	2.23	5	5.93	186	0.91
Phocid pinnipeds (PW) underwater (NMFS, 2024)	40 Hz – 90 kHz	1.63	5	0.81	68.3	0.29

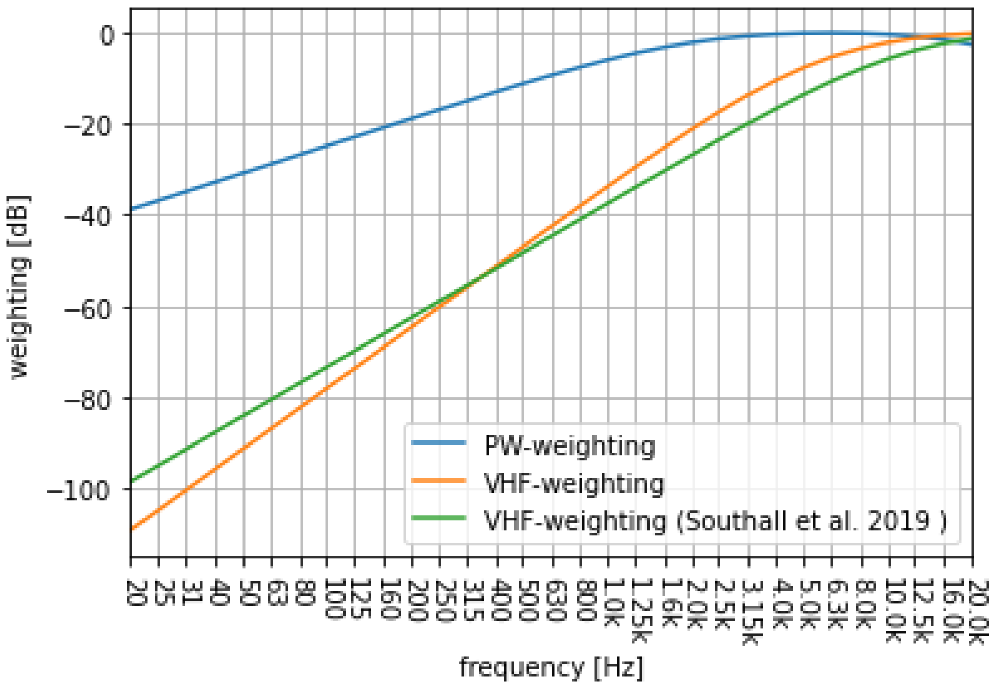

Figure D-2 **Comparison of weighting functions for cetacean groups using VHF sounds and the PW-weighting**

Appendix D.4 Impact ranges and areas

The impact range defines the confined area, in which specific animals are affected by the noise. This region was called the impact area A_{impact} and was calculated by adding all angular sectors with the radius r_i provided by the distance to the impact thresholds.

$$A_{impact} = \sum_{i=1}^{72} \pi r_i^2 \frac{d\alpha}{360°}$$

Angular resolution was used for the angular resolution $\alpha = 360°/72 = 5°$.

D. Feasibility of Wind Farm and Fish Farm Coexistence

OFFWOFF – Feasibility of windfarm and fish farm coexistence

Technical, operational, biological and commercial feasibility study for joint development of a floating windfarm and a submerged fish farm at Mareld

In cooperation with Freja Offshore, DHI, ÅKP and Fyrbodals kommunalförbund

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1	14.05.25	Final	Paal Hylin Morten Lyssand	Karl Christian Strømsem	Karl Christian Strømsem
Rev	**Date**	**Document Status**	**Prepared by**	**Reviewed by**	**Approved by**

NO-2025-001-R001 Click here to enter text.

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NO Doc. No.
NO-2025-001 | 00

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DOCUMENT ISSUE RECORD

Rev	Date	Status	Prepared by	Reviewed by	Approved by
1	04.05.2025	Draft	Morten Lyssand and Paal Hylin	Karl Christian Strømsem	

Document Change Record

Rev	Section(s)	Page(s)	Brief Description of Change
1	All	All	Original Issue to Client

Document HOLD Record

Section(s)	Page(s)	Brief Description of HOLD
N/A		

1. EXECUTIVE SUMMARY

This report presents the results of SUBFARM AS's work under the OFFWOFF project—"Offshore Floating Wind and Offshore Fish Farm"—with a focus on assessing the feasibility of co-locating submerged aquaculture systems within the perimeter of floating offshore wind farms. The project is a Nordic Innovation–funded collaboration involving Freja Offshore, DHI, ÅKP, and Lysekil municipality, with SUBFARM responsible for delivering Work Package 1 (Technical, Operational, and Biological Feasibility) and Work Package 4 (Business Plan Updates).

The Mareld offshore wind farm in Skagerrak, currently under evaluation by Freja Offshore, serves as the project's pilot case. SUBFARM proposes deploying multiple "SubFarm" submerged aquaculture units within the Mareld wind farm area, aiming to co-produce renewable energy and farmed Atlantic salmon in a shared offshore zone.. With a total estimated production of more than 50,000 tons per year, the project could significantly bolster Sweden's domestic food supply and reduce import dependence

The study confirms that the technical integration of SubFarm systems with the planned wind turbine layout at Mareld is feasible. Analyses show that mooring conflicts with turbines and cables can be avoided with careful spatial planning. Operationally, the fish farms and wind farm can largely operate independently, with some synergy potential identified in logistics, vessel use, and shared land-based infrastructure. Biological assessments indicate that Mareld meets key environmental parameters (temperature, salinity, oxygen) needed for salmon farming, although further measurements of deepwater oxygen and current duration are recommended.

From a regulatory and stakeholder perspective, the co-location concept presents both opportunities and challenges. Engagement with local fishing communities, municipalities, and environmental stakeholders is essential. The co-location model could create significant economic value, with estimates showing over 5,000 potential jobs and SEK 8–9 billion in value creation for the Swedish west coast, modeled on the economic ripple effects of Norway's Rogaland aquaculture sector.

The financial viability of offshore aquaculture at Mareld is promising. Conservative modeling shows that an investment of NOK 4.7 billion could yield a net present value (NPV) of NOK 4.2 billion and an internal rate of return (IRR) of 19%, with annual net cash flows reaching NOK 1.8 billion after full deployment. The business case is bolstered by strong demand for locally produced salmon, proven Norwegian aquaculture cost structures, and the strategic alignment with Sweden's renewable energy and food security goals.

In conclusion, this report finds that the co-location of floating wind power and submerged fish farming is technically feasible, biologically viable, and economically attractive. The Mareld case study illustrates how strategic, sustainable use of offshore space can support green growth, innovation, and value creation across multiple sectors. Realizing this potential will require targeted investments, regulatory adaptation, and continued stakeholder dialogue.

2. INTRODUCTION AND BACKGROUND

This report documents SUBFARM AS's contributions to the OFFWOFF project—"Offshore Floating Wind and Offshore Fish Farm"—through its leadership and execution of Work Package 1 (Technical, Operational and Biological Feasibility) and Work Package 4 (Business Plan Updates). The project is part of a joint initiative to explore the technical and commercial viability of co-locating submerged fish farms within the perimeter of floating offshore wind farms. It is funded under the Nordic Innovation framework and involves a consortium including Freja Offshore, DHI, ÅKP, and Lysekil municipality.

The project is motivated by a growing need for more efficient marine spatial planning and for sustainable, co-located ocean industries. Offshore floating wind energy and aquaculture are both experiencing rapid expansion but face growing spatial, environmental, and operational constraints. In response, the OFFWOFF project seeks to evaluate whether and how these industries can coexist within the same maritime footprint, thereby optimizing use of offshore areas while advancing environmental, economic, and societal goals.

The focal case study is the Mareld offshore wind farm, located in the Skagerrak approximately 40 km west of the Swedish coast. Freja Offshore is developing Mareld as a floating wind park with a planned capacity of up to 2.5 GW. SUBFARM, in turn, proposes deploying submerged aquaculture systems—known as SubFarm units—within the wind farm perimeter. These systems are engineered for deep-water, high-energy environments and are designed to meet stringent criteria for fish health, welfare, and operational safety.

Chapter 3 describes the SubFarm fish farming concept in detail, including technical specifications of the cage and feed platform systems, as well as the proposed field layout and installation procedures. Chapters 4 build on this by identifying operational synergies with the wind farm (e.g. shared logistics and inspection infrastructure), and by assessing biological feasibility with regard to water quality, sea lice, disease control, and fish welfare.

Chapter 6 presents a stakeholder assessment, highlighting the interests of fishing communities, municipalities, regulators, and environmental groups. The assessment identifies opportunities and risks associated with integrating aquaculture into offshore energy zones, including effects on biodiversity, marine ecosystems, and local economic development. Finally, Chapter 7 evaluates the economic potential of offshore fish farming in Sweden, including a case comparison with Norway's Rogaland region.

The work conducted by SUBFARM in WP1 and WP4 forms the technical and commercial backbone of this assessment. WP1 established the baseline feasibility of co-locating submerged aquaculture systems with floating wind turbines, addressing both environmental compatibility and operational integration. WP4 used these findings to update system designs and logistics plans, and to produce a business case supporting full-scale implementation. Together, these work packages demonstrate that a well-planned and coordinated approach to co-location can unlock new value from offshore areas, while supporting the broader goals of sustainability, food security, and renewable energy expansion.

3. FISH FARMING CONCEPT

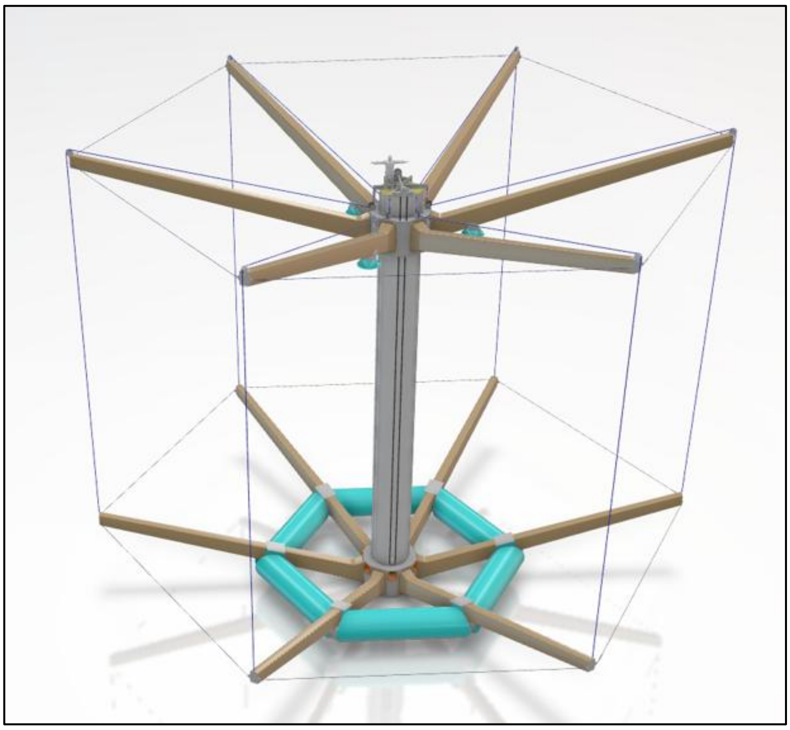
3.1 Description of the fish farm

The SubFarm system presents an innovative approach to offshore aquaculture, diverging from conventional surface-based steel structures typically used in exposed marine environments. Instead, it employs a low-profile surface feed platform and up to twelve submerged cages suspended around it. This configuration reduces visual and spatial footprint, improves resilience to harsh weather, and enhances fish welfare.

Each cage measures approximately 40 meters in diameter and 35 meters in depth, offering a total volume of 40,000 cubic meters. This allows for the cultivation of up to 200,000 salmon or trout per cage. A single point mooring system connects each cage to the seabed and is operated by an integrated winch. This enables precise vertical positioning of the cages in the water column to avoid surface turbulence or to locate optimal environmental conditions. The submerged design not only shields fish from surface conditions but also reduces escape risk and interaction with surface predators

A structural design of the SubFarm cage is shown in Figure 1.

Figure 1 Illustration of the SubFarm cage



The feed platform is based on Sevan Deepwater Technology's circular design and comes in different versions dependent on wave height and storage capacity. For the Mareld field the size is 17m height and 26m in diameter. The feed platform is moored with three pairs of catenary mooring lines. Figure 2 shows an illustration of the feed platform.

The cages are positioned dynamically in the water column on different water depths to avoid forces from waves or to find the best biological water conditions. Every cage is connected to the feed platform via an umbilical. The umbilical provides feed, electric power and air, and contains a data cable for control and monitoring. The umbilical also acts as an extra mooring line if the single point mooring should break.

Each cage can hold up to 200.000 fish of 5 kg, giving the production capacity of one farming system up to 12.000 tons.

Figure 3-5 shows illustrations of the SubFarm systems

Figure 2 Sevan Deepwater Technology feed platform

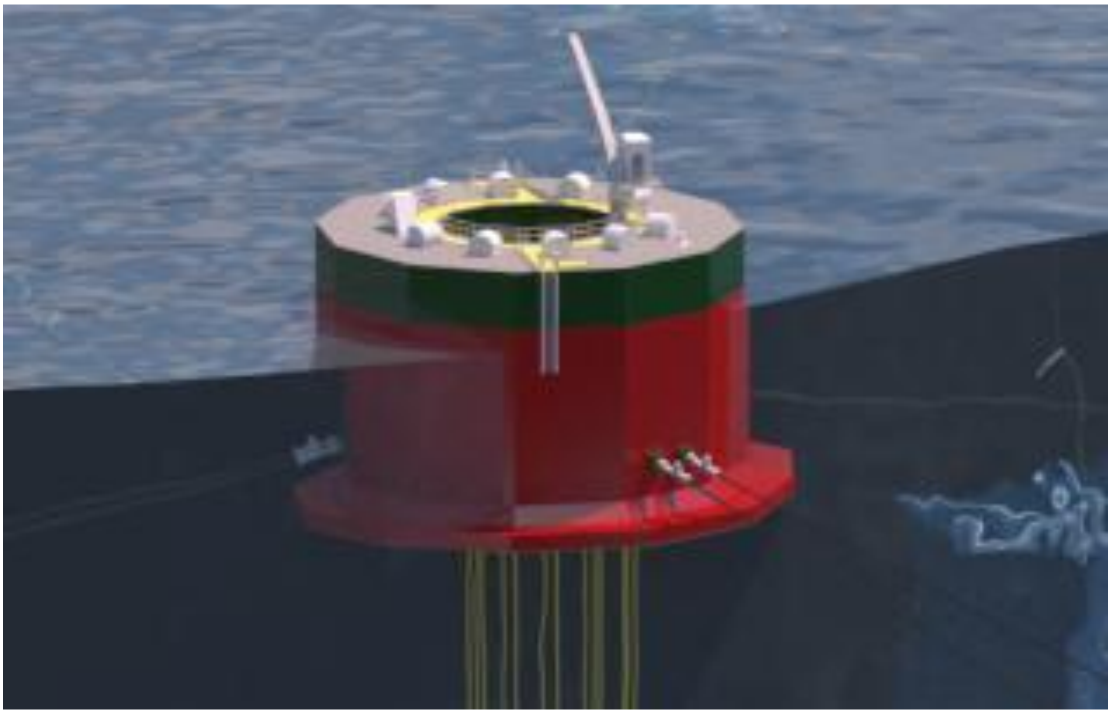


Figure 3 Overview of the SubFarm

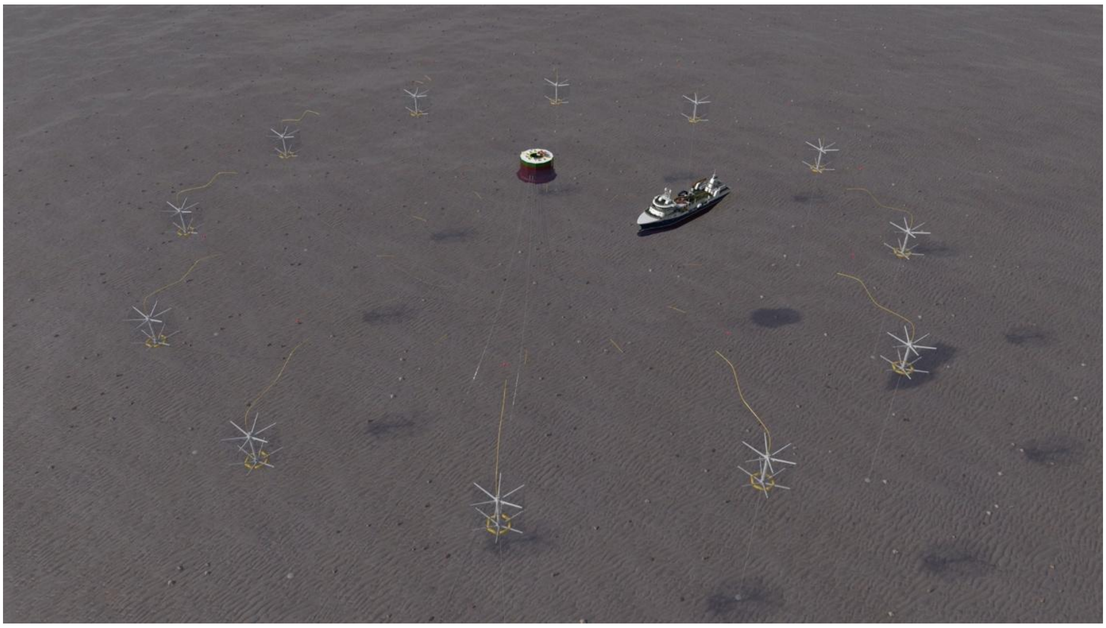


Figure 4 Overview of the SubFarm seen from the sea floor

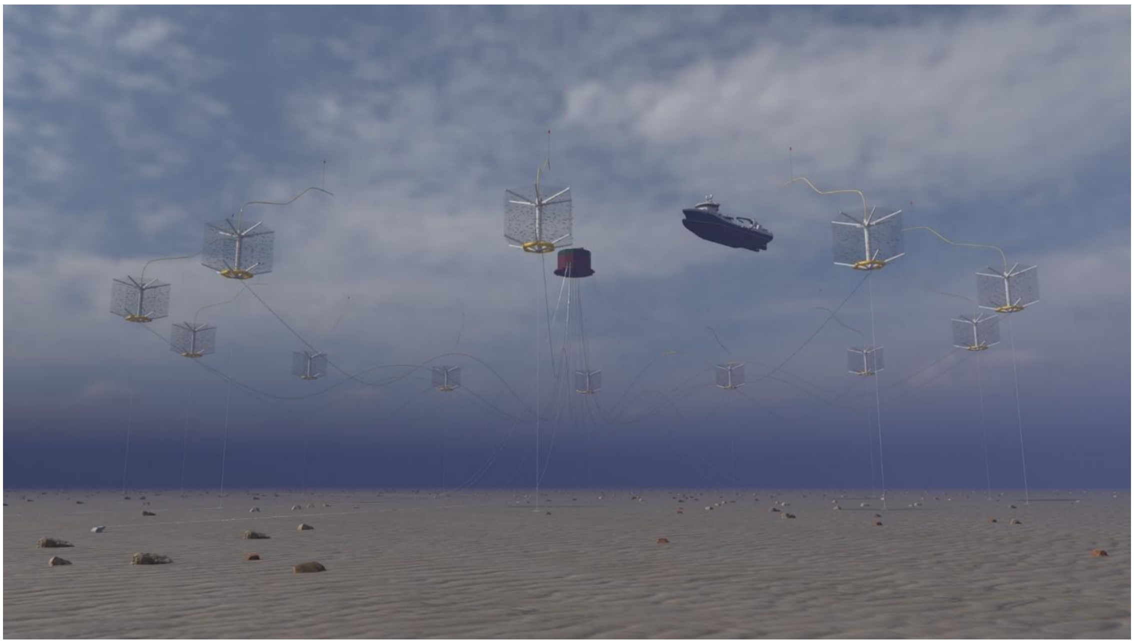
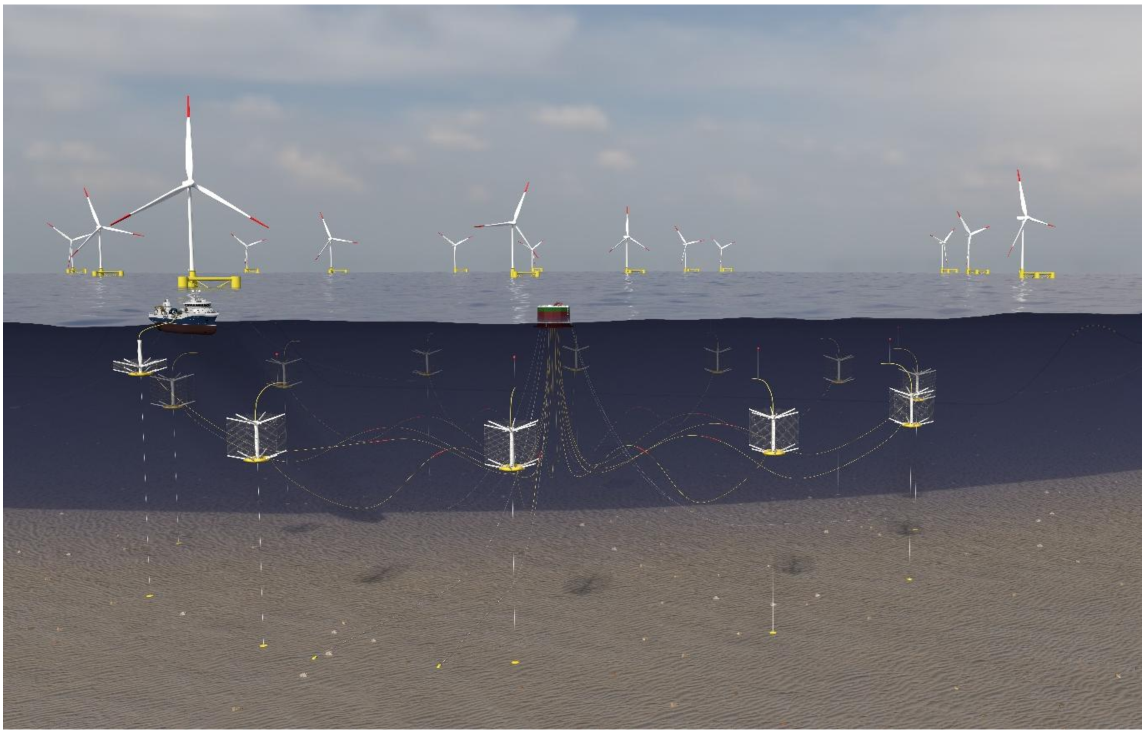


Figure 5 SubFarm Co-located with floating wind turbines.



The metocean requirements for SubFarm are listed in Table 1.

Table 1 SubFarm metocean requirements

Sea state	Requirement
Water depth	> 100m
Water current	< 1m/s
Wave height [Hs]	< 10m

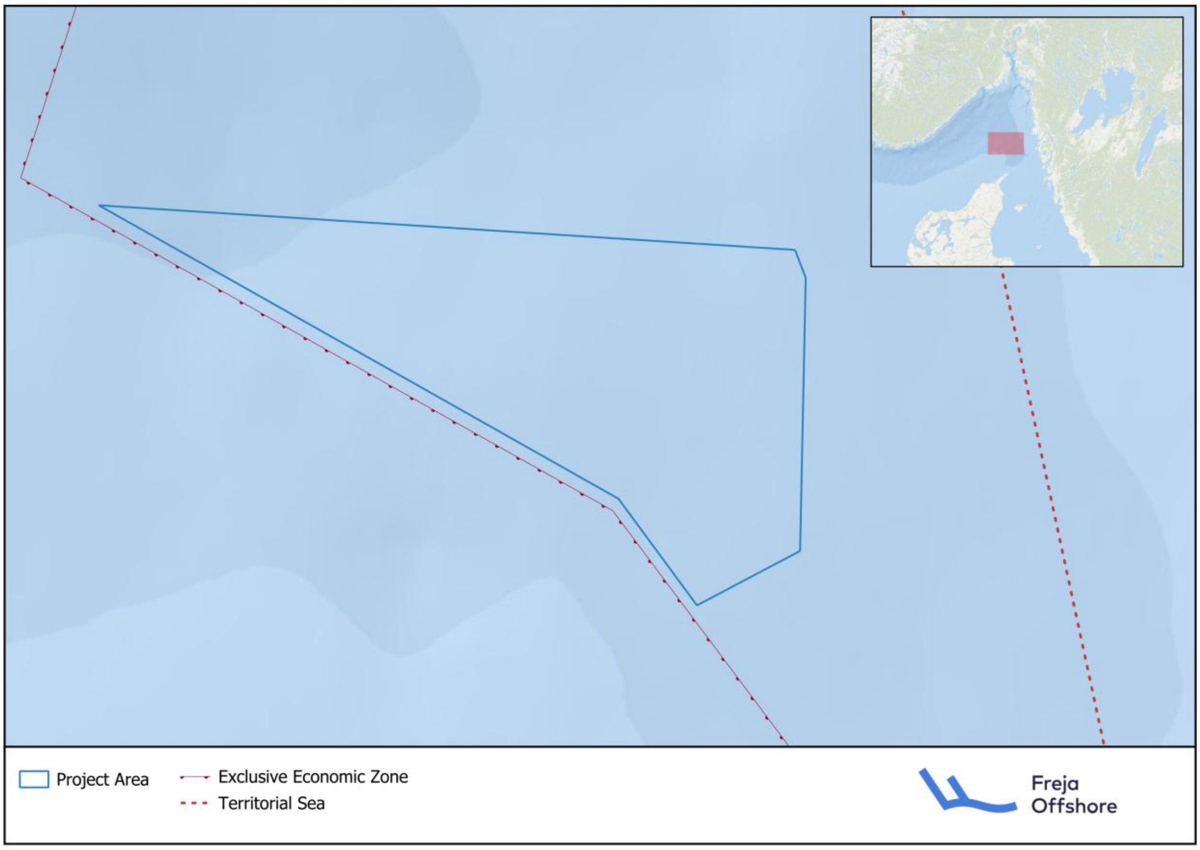
3.2 Mareld windfarm field layout

3.2.1 The Mareld field

The Mareld offshore wind farm site, situated roughly 35 kilometres west of the Swedish mainland in the Skagerrak, offers depths exceeding 100 meters—ideal for submerged aquaculture systems.

Figure 6 illustrates the boundaries of the Project Site

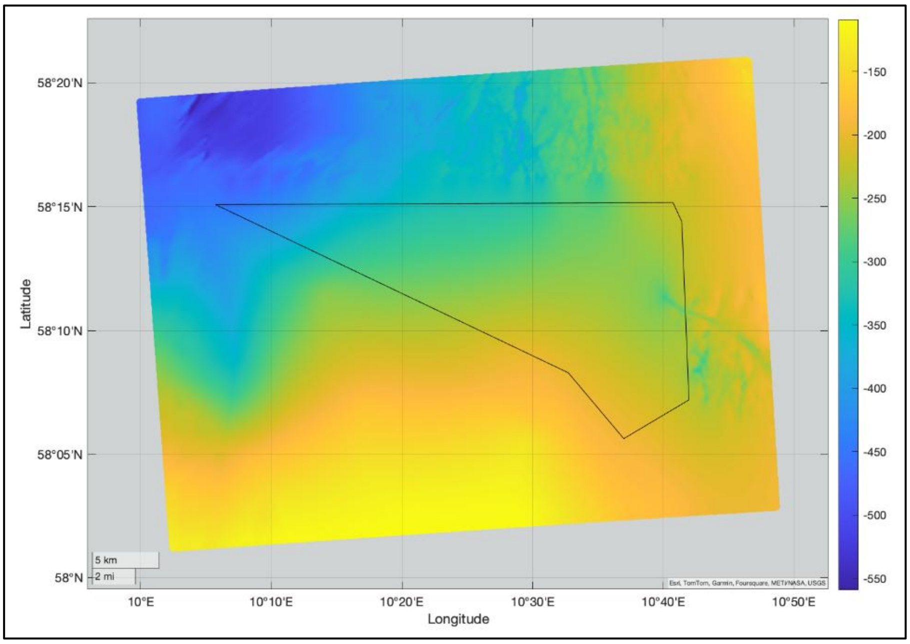
Figure 6 The Mareld field layout



Bathymetric conditions and hydrodynamic profiles suggest that the site can accommodate multiple SubFarm units while maintaining safe distances between fish farms and wind turbine infrastructure.

The bathymetry for the area is shown in Figure 7

Figure 7 Mareld Bathymetry Detailed



3.2.2 Co-location at the Mareld field

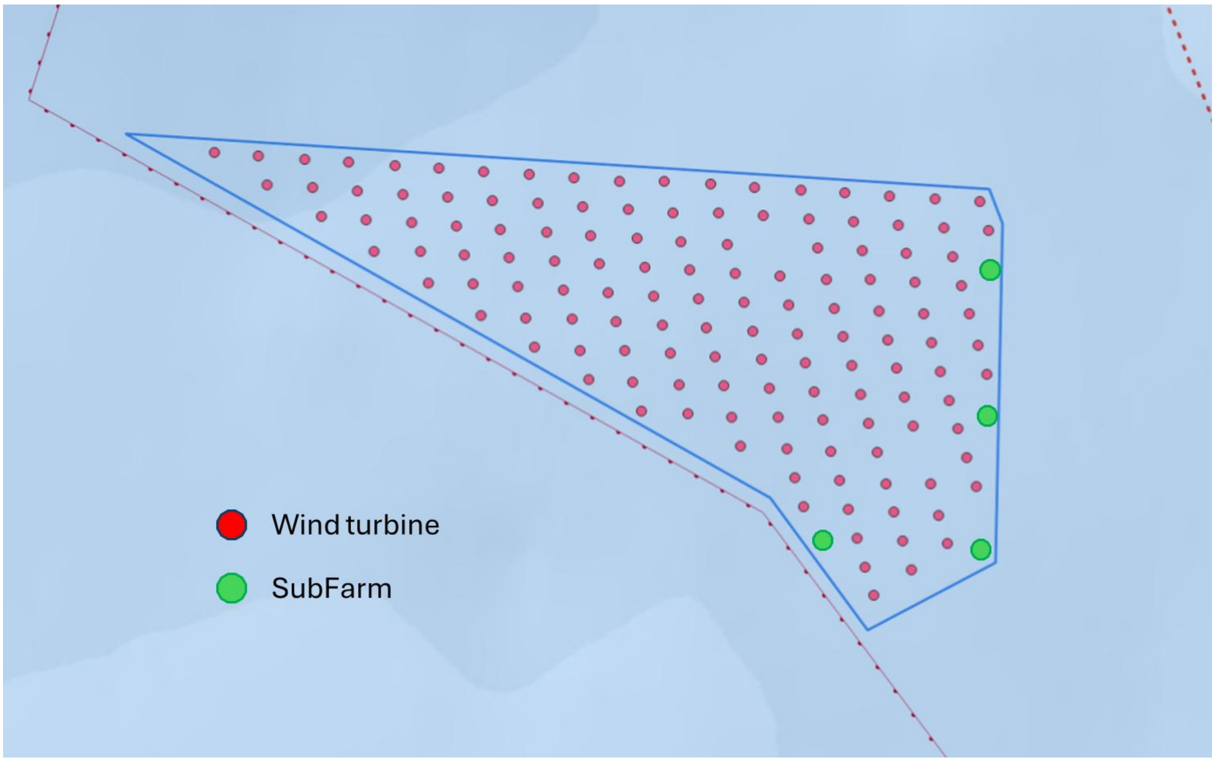
It is proposed to install four SubFarm units within the wind farm perimeter, resulting in a combined production capacity of 48,000 tons annually, see Figure 8. For context, Sweden's annual consumption of fresh salmon is approximately 5,000 tons, implying that this offshore facility could significantly contribute to domestic food security and reduce dependency on imports.

The layout design emphasizes:

- Shortest possible distance to shore
- Locating farms where wave heights and currents are most favourable,
- Ensuring minimum 4 km separation between units to mitigate the risk of disease transmission,
- Avoiding interference with turbine mooring lines and inter-array cables,
- Minimizing overlapping operational footprints.

Potential impacts of turbine noise on fish welfare are being addressed in a separate noise impact assessment conducted by DHI.

Figure 8 Number of fish farms (green circles) planned for the Mareld field



The largest uncertainties by co-locating offshore floating wind turbines with offshore fish farming are the following:

1. Is it possible to install (moor) the fish farm within the perimeter of the wind park without mooring lines come in conflict with the wind turbine mooring lines or inter-array cables.
2. Can operations of the wind park and the fish farm be carried out without any interruption on the other part.
3. Are there any noise from the wind park that may inflict on the fish welfare (see report from DHI on noise)

Chapter 3.3 and 3.4 will address the two first. The report on noise from DHI will analyse the latter.

3.3 Installation

Co-locating aquaculture systems with wind turbines requires thorough analysis of spatial and mooring dynamics.

1. Size of the wind turbine and distances between them. A 15 MW turbine will need larger distances in between, typically 1.5-2 km, to reduce wind wake and increase

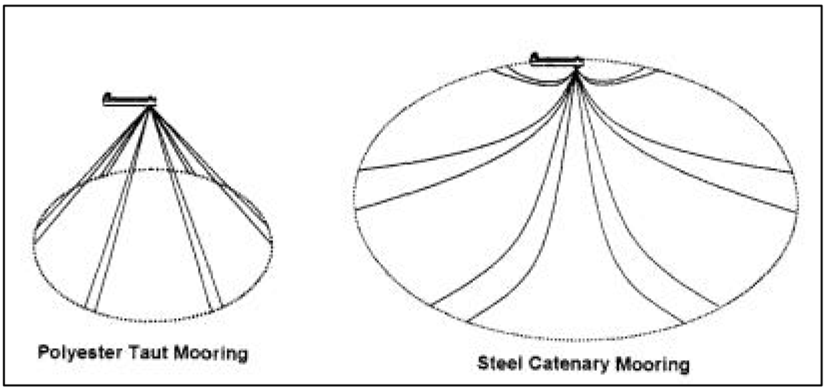
overall performance of the park. Inherently, larger turbines will therefore give more space for a fish farm.

2. Size and design of the fish farm. In general, the mooring line spread of a subsurface system will be less than that of a larger surface-based structure. The mooring footprint of a SubFarm system is therefore smaller, which reduces the likelihood of conflicts with the turbine infrastructure.

3. Seabed characteristics—such as sediment type and topography—are critical in determining whether suction anchors (with minimal horizontal spread) or traditional catenary chain systems can be used. These choices influence the overall layout and ensure safety and stability under dynamic loading conditions, See Figure 11 below.

4. Water depth. Larger water depths will in general need longer mooring lines both for the turbine and the fish farm. Larger depths may therefore result in a conflict of mooring lines

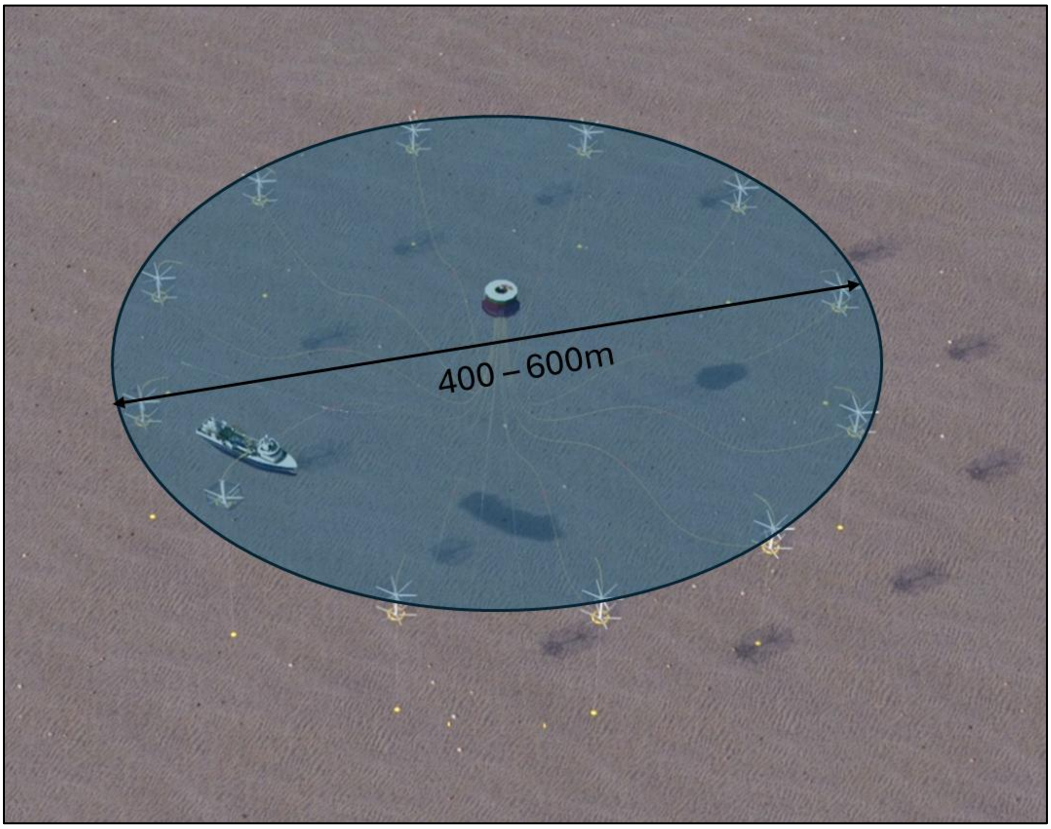
Figure 9 Difference between tout and catenary mooring



A typical horizontal radius of a tout mooring system would be 6-700m depending on water depths and allowable horizontal movement of the turbine. For a catenary mooring system, the horizontal radius would be ~1000m.

A SubFarm mooring system typically spans a horizontal footprint of 400 to 600 meters. This size allows the units to fit within the buffer zones between wind turbines without violating turbine safety radii (typically 500 meters). See Figure 10 for illustration

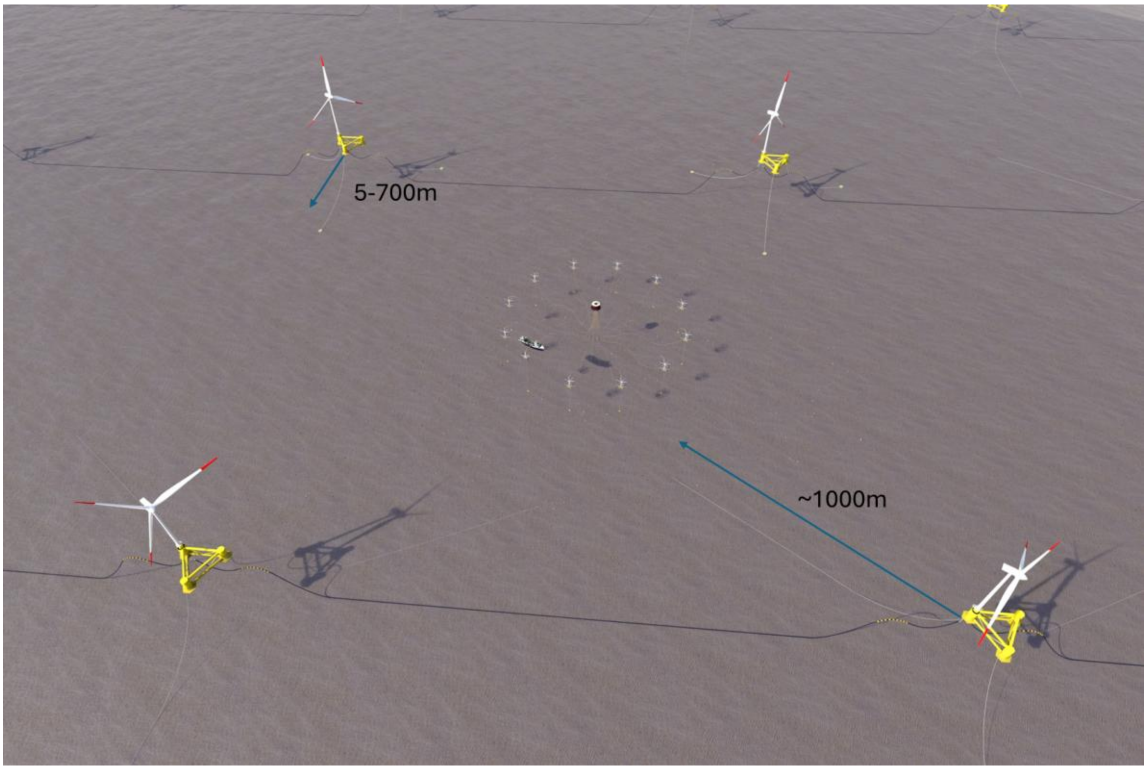
Figure 10 Size of the SubFarm system in horizontal direction



Through iterative simulations and stakeholder input, the final layout will optimize both turbine efficiency and fish farm operability. Collaboration between the wind and aquaculture developers is essential to define shared zones, emergency response protocols, and infrastructure access routes.

The SubFarm system could be placed into the wind farm park as illustrated in Figure 11.

Figure 11 lay out of the wind mill park mooring lines and cables

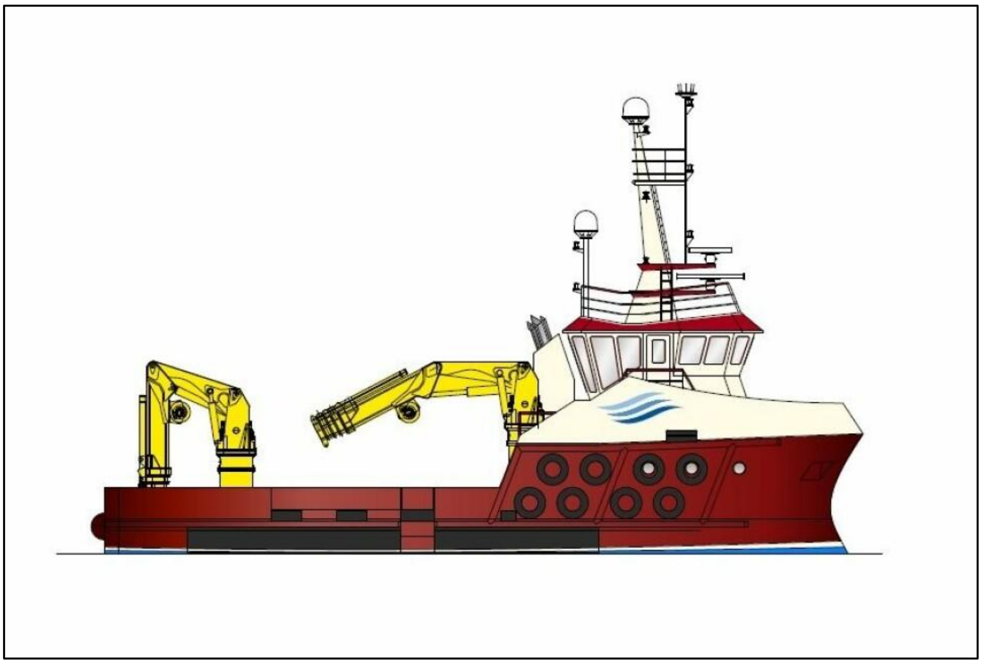


3.4 Operations

With a safety zone of 500m around each wind turbine none of the operations for the SubFarm's will be within that safety zone. The closest operations will be when transfer smolt, harvest, outtake of samples or dead fish, transfer of feed (pellets) and other supplies. In addition, there will be some maintenance and ROV inspection offshore. However, these operations will take place during calm weather. The transfer of smolt and harvest will be carried out by a well boat (up to 100m long) with either DP class 2 or 3, see Figure 12**Error! Reference source not found.**. The other operations will be carried out with larger workboats with a typical size of 30m, See Figure 13.

Figure 12 Typical well boat for transporting live fish in the aquaculture industry

Figure 13 Work boat for general operations on the cage such as sampling of fish and ROV operations



In addition to these operations towing of and installation/removal of cages will take place. This will be carried out yearly or every second year. This operation will be carried out by the workboat. These operations will be done during very calm weather. The cage will be floated in and surfaced position and towed to from the offshore farm, see Figure 14.

Figure 14 towing of cage to and from the offshore farm

The support of the feed platform will be more frequent but will be at a distance of 1000m or more to the wind turbines. These operations includes supply of feed, fuel and personnel. Typical vessels for these operations are a pellets carrier and a crew transport vessel (CTV). The CTV could be the same as the one used for the wind park. See Figure 15 and Figure 16.

Figure 15 Typical pellets carrier for the aquaculture industry.

Figure 16 Crew transport vessel for carrying personnel to the SubFarm.

In Table 2 you will find a table of activities and frequencies:

Table 2 Operational activities

Scheduled activities	Frequency	Vessel type
Transfer of smolt (fry)	Annually (10-20 voyages)	Well boat
Harvest	Annually (10-20 voyages)	Well boat
Transfer of feed	Monthly	Pellets carrier
Taking samples	Every second month	Work boat
Other supplies	Monthly	Work boat
Maintenance & inspection	Annually	Crew vessel/work boat
Dead fish collection	Weekly (or often as possible)	Work boat

The most critical operations will be with the well boat, the pellets carrier and during installation/removal of cages and the towing to and from the field. These operations have to be planned, and operational procedures has to be in place. A training simulator should also be used to train on these specific operations.

3.5 Operational synergies

There are four areas where there are operational synergies with the wind park.

1. During installation
2. Operation of the CTV
3. ROV inspections
4. Land base

3.5.1 Installation campaign

During installation campaign the pre lay of anchors and mooring lines for the fish farm can be done by the same vessels as the wind park will use. The planning and execution could be planned together to save time and cost for both projects.

3.5.2 Crew transfer and ROV inspections

As described in chapter 3 the fish farm needs specialised vessel for support. Only the Crew transport vessel can be used both for the fish farm and the wind park.

3.5.3 Land base

The land base can be shared between the wind park and the fish farm. Accommodation and storage, quay side and other facilities can be shared to reduce investment and operational cost.

4. BIOLOGICAL FEASIBILITY

One of the world's most important farmed species is Atlantic salmon. The salmon's great popularity is due to its relatively easy handling, reproduction, rapid growth, high commercial market value, and extreme flexibility in adapting to different and often varying farming environments. Atlantic salmon is farmed, partially protected from the sea, along the coasts of Europe, North America, Chile, and Tasmania. Global production has risen steadily from about 0.2 million tons in 1990 to more than 2.8 million tons in 2022. (FAO.org)

4.1 Water quality

Water quality and protected areas are the main drivers for the increase in Atlantic salmon production. However, new protected areas with the right water quality are limited and the industry is looking for more exposed and offshore location to further increase production.

The main parameters for water quality are the following.

1. **Water temperature.** Atlantic salmon thrives best and has the best growth rates in water temperatures 8-16° C. For the welfare, the temperatures can go as low as 3° C and up to 20° C. Above 23° C the mortality risk increases.

2. **Salinity.** Atlantic salmon is an euryhaline species and can live in both fresh and salt water. However, there is an upper limit of salinity that the salmon will thrive in. There is little research on the max salinity a salmon can survive. However, the North Atlantic has a salinity of 33-37 ppt (NOAA.gov).

3. **Water current.** The water currents should be neither too low nor too high over a longer period (>3-5 hours). There is not much research on the too low currents, and it will depend on the size of the cage and number of fish and oxygen saturation. Smaller cages (200.000 fish) are favorable over large cages (up to 1.5 M fish). A rule of thumb is that the water currents should not be lower than 0,05 m/s for more than 3 hours. When it comes to max water currents, the research is more complete (Havbasert oppdrett – hvor mye vannstrøm tåler laks og rensefisk?, Havforskningsinstituttet). From this research the max water currents should not exceed 0.8 m/s and duration less than 4 hours.

4. **Oxygen level.** The level of oxygen saturation needed to keep a good fish welfare for the salmon will vary with temperature and stress level. Under normal conditions a saturation of >80% will keep good fish welfare (Nofima). However, to achieve good growth the saturation should be above >100%.

In the following we have used data from the EU database Copernicus (https://data.marine.copernicus.eu) to evaluate the four different water quality parameters for the Mareld field. The Copernicus data that we can retrieve is from

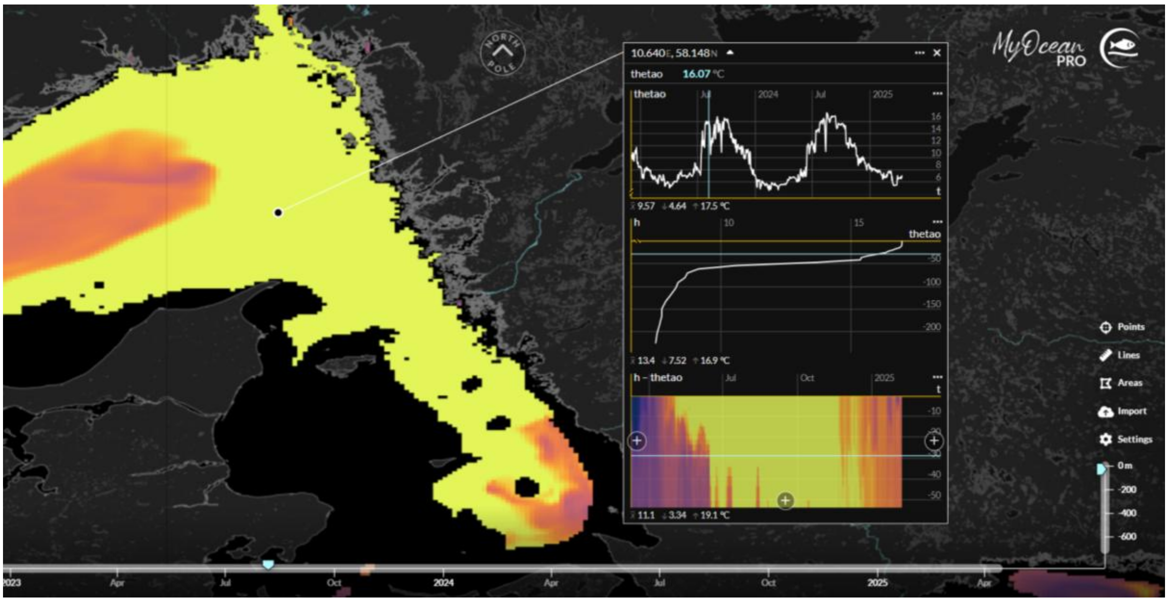
October 2022 for temperature, salinity and current. For Oxygen saturation we can only access data from one month back in time.

4.1.1 Water temperature

Table 3 Water temperatures at surface and at 50 meter water depth

Temperature	Surface (0m)	Subsurface (-50m)
Mean	10.4° C	9.0° C
Minimum	4.6° C	5.6° C
Maximum	17.7°	15.2° C

Figure 17 Water temperature at the Mareld field

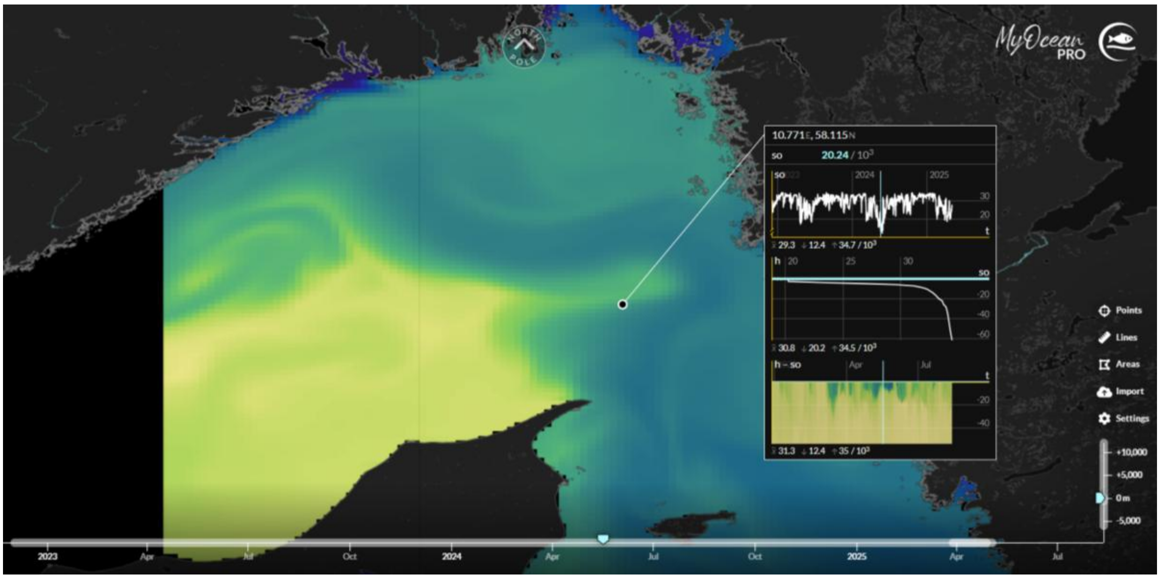


4.1.2 Salinity

Table 4 Salinities at Mareld

Salinity	Surface (0m)	Subsurface (-50m)
Mean	29.5 ppt	34.3 ppt
Minimum	13.7 ppt	32.5 ppt
Maximum	34.6 ppt	35.7 ppt

Figure 18 salinities at Mareld

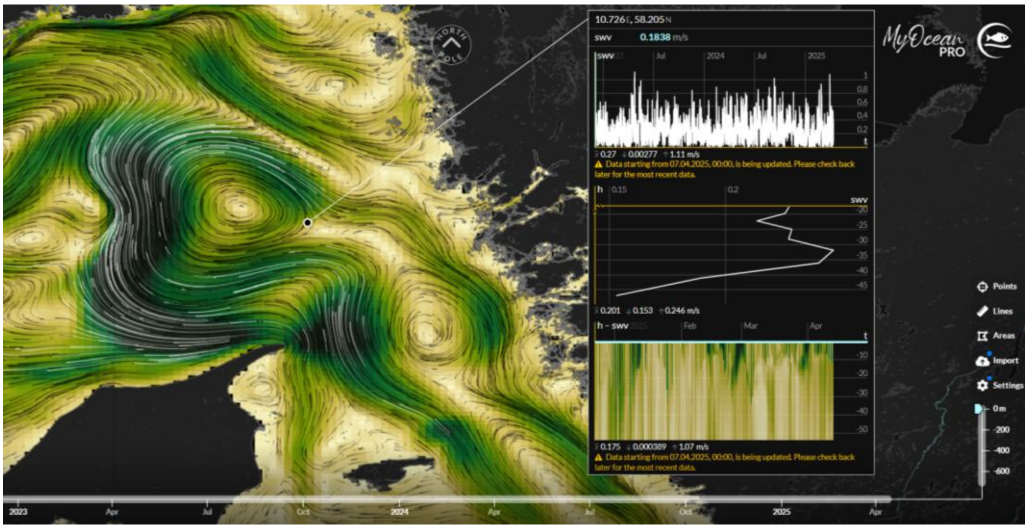


4.1.3 Sea Currents

Table 5 Sea currents at Mareld

Sea currents	Surface (0m)	Subsurface (-50m)
Mean	0.2 m/s	0.15 m/s
Minimum	0.01 m/s	0.002 m/s
Maximum	0.7 m/s	0.48 m/s

Figure 19 Sea currents at Mareld

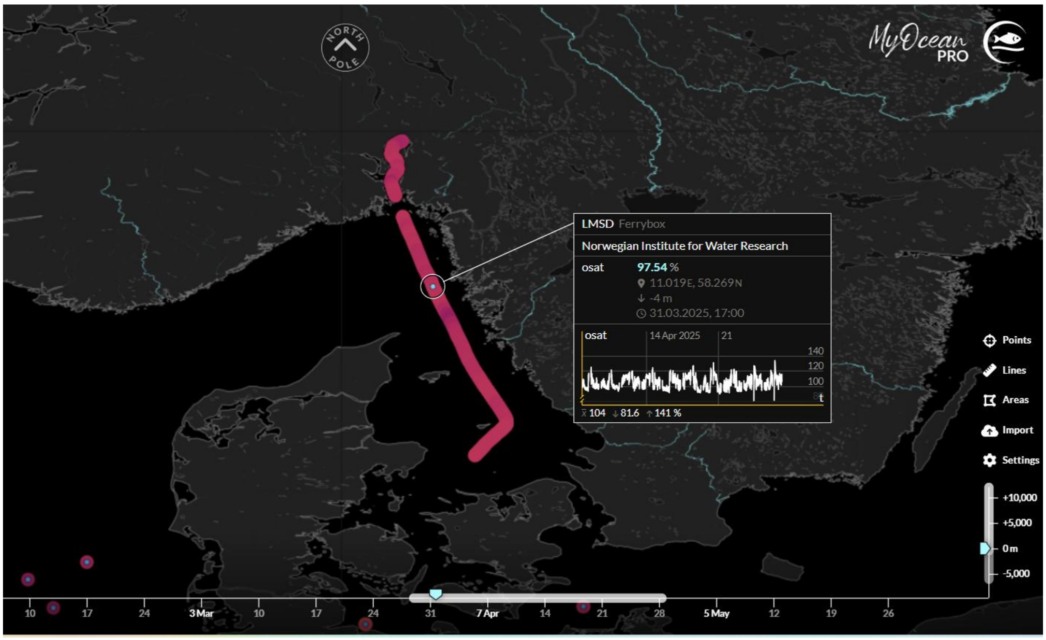


4.1.4 Oxygen levels

Table 6 Oxygen levels at Mareld at surface and at 50 meters water depth

Oxygen	Surface (0m)	Subsurface (-50m)
Mean	104 %	No data
Minimum	82 %	No data
Maximum	141 %	No data

Figure 20 Oxygen levels at Mareld



4.1.5 Water quality conclusion

The water quality parameters are within the limits when it comes to temperature, salinity and oxygen saturation. However, the data points on the oxygen saturation are limited but the indication is that there is sufficient oxygen to farm Atlantic salmon.

When it comes to sea current the picture is different. It seems that the sea current speed can be too low. However, there is no data on the duration and if this will last for hours.

To be confident that the water quality is sufficient for farming Atlantic salmon, a more thorough investigation on sea currents and oxygen levels in the depths must be carried out. Therefore, a prolonged measuring of these parameters at the location at several water depths must take place before planning farming of Atlantic salmon in the Mareld field.

4.2 Sea lice

Sea lice are still the biggest health and welfare problem in Norwegian farming. In offshore farming conditions, it is expected that this problem will be significantly less at Mareld as the important contamination from other surrounding facilities will be minimised. Infection with lice will have to be expected, but it will largely be possible. "washed" out of the facility. The uncertainty relates to whether an offshore facility will be able to develop into a "lice producer" and have a negative impact on the ecosystem. Submersible facilities will largely eliminate this potential problem. Data from the Norwegian Institute of Marine Research and industry support this.

4.3 Other infectious diseases

Several of the most important infectious diseases in aquaculture (PD, ILA) have other farmed fish as their main reservoir for infection. With a considerable distance to other aquaculture facilities, it is expected that this infection pressure will be reduced.

For other diseases, the reservoir of infection is more complex and linked to wild fish and other marine ecosystems. Examples of this are bacteria that cause vibriosis and cold-water vibriosis, and several pathogenic bacteria. Vaccination should be essential in areas where effective vaccines are available to combat these diseases.

The amoeba parasite that causes AGD (Amoebic Gill Disease) represents a particular challenge. Its life cycle is not fully understood, but the parasite thrives in high salinity and relatively high temperatures. The infection can also be found in deep water, and submersible facilities cannot expect to escape this challenge. Offshore facilities should plan a treatment strategy to address this logistical challenge.

4.4 Inspection and fish health control

This is a crucial point. Real offshore locations will significantly complicate traditional fish health inspections. Intense efforts are being made to develop automatic monitoring systems, but they are still not well-developed enough. It is important to continue this work in close collaboration between fish health services, the industry, and research environments. Facilities must have systems (traditional/indicators/automation) that allow them to quickly detect health/welfare issues, especially regarding problems that can cause mass mortality and the handling of large quantities of dead fish.

4.5 Genetics and smolt quality

The rougher farming environment of offshore facilities may require the development of smolts that are better adapted in terms of size, genetics, and physiology.

5. STAKEHOLDER ASSESSMENT FOR THE MARELD OFFSHORE WIND AND AQUACULTURE CO-LOCATION PROJECT

5.1 Overview

The Mareld project proposes a 2.5 GW floating offshore wind farm situated approximately 40 km west of Lysekil, Sweden. Anticipated to generate up to 12 TWh annually, Mareld aims to contribute significantly to meeting West Sweden's escalating electricity demands, which are projected to double by 2030 due to industrial electrification (source: mainstreamrp.com).

In an innovative approach to marine spatial planning, the project integrates offshore wind energy production with sustainable aquaculture. This co-location strategy involves deploying a number of fish farm systems with submersible cages between wind turbine towers. Each system comprising of a feed platform and 12 cages capable of producing approximately 12,000 tonnes of fish per year. The initiative is part of the OffWoff (Offshore Floating Wind and Offshore Fish Farms) co-location project, supported by Nordic Innovation.

5.2 Key Stakeholders and Interests

Table 7 Key stakeholders

Stakeholder Group	Level	Role/Interest
Local Fishing Communities	Local	Concerns over access to traditional fishing grounds and potential livelihood impacts.
Coastal Municipalities	Local	Economic development, employment opportunities, and environmental considerations.
Marine Businesses	Local	Opportunities in logistics, maintenance, and supply chain services.
Environmental Organizations	Local/Regional	Monitoring ecological impacts and advocating for sustainable practices.
Regulatory Authorities	Regional	Oversight of compliance with marine spatial planning and environmental regulations.
Research Institutions	Regional	Engagement in innovation, data collection, and advancement of marine technologies.

5.3 Impact Analysis

5.3.1 Economic Impacts

Positive:

- The co-location model is expected to create approximately 60 jobs per fish farming system—30 offshore and 30 onshore—thereby stimulating local economies (source: nordicinnovation.org).

Challenges:

- Local businesses may face scalability issues to meet increased demand.
- There may be uneven access to newly created skilled positions.

5.3.2 Environmental Impacts

- Positive:
  - Offshore wind farms can function as artificial reefs, potentially enhancing marine biodiversity.
- Challenges:
  - Potential risks include pollution or habitat disturbance if not properly managed.
  - Rigorous environmental monitoring is required.

5.3.3 Social Impacts

- Positive:
  - The project positions local communities as hubs of green innovation.
  - Potential for infrastructure upgrades and increased tax revenues.
- Challenges:
  - Perceptions of exclusion if benefits are not equitably distributed.
  - Need for transparent stakeholder engagement.

5.4 Sector-Specific Considerations: Aquaculture and Offshore Wind Co-Location

- Impact of Offshore Wind Turbines: Noise and vibrations can affect fish behavior, stress levels, and health.
- Construction Disruptions: Increased noise, emissions, and vibrations during construction can disturb marine ecosystems.
- Risk of Collisions and Disease Spread: Higher shipping activity could increase vessel collision risks and disease transmission.

- Electromagnetic Fields (EMF): Subsea cables and turbines generate EMFs whose effects on farmed fish need further research.
- Mitigation through Best Practices: Proper planning, design, and operations can minimize negative impacts.

5.5 Recommendations

- Stakeholder Engagement: Implement inclusive consultation processes to address concerns and inputs.
- Environmental Monitoring: Establish comprehensive monitoring programs.
- Economic Development: Develop training and capacity-building initiatives.
- Research Collaboration: Foster partnerships with research institutions.

5.6 Conclusion

This stakeholder assessment underscores the multifaceted implications of the Mareld project, highlighting the necessity for balanced and inclusive approaches to marine resource utilization. The successful co-location of offshore wind and aquaculture activities requires continuous stakeholder engagement, rigorous environmental stewardship, and proactive capacity building to ensure sustainable development in the Mareld offshore area.

6. ECONOMIC INCENTIVES AND VALUE CREATION POTENTIAL OF FISH FARMING FOR WEST COAST SWEDEN

6.1 Introduction

Establishing a new industrial value chain for salmon production on the Swedish west coast will require the development of a series of offshore, onshore and marine logistics infrastructure and services. The combined economic impact of such new industry will be important.

The purpose of this chapter is twofold:

1) Demonstrate the attractiveness of investing in an offshore fish farming project inside the perimeter of the Mareld offshore wind project; and
2) Indicate the direct and indirect value creation potential for the west coast of Sweden by opening up for offshore fish farming in its waters.

6.2 Investment opportunity

In analysing the attractiveness of investing in an offshore fish farm inside the perimeter of the Mareld offshore wind project, we will assume that the area Mareld area can accommodate four SubFarm production systems, each with an annual production capacity of 12 thousand tons of salmon. For biological and operational testing purposes it is recommended to carry out an early production test with a capacity of up to 3 thousand tons, which later can be included in the full development program. Hence, total annual production capacity from the Mareld fish farming development will be 51’ tons

6.2.1 Capital costs (CAPEX)

The SubFarm capital costs include:

- Detailed engineering, construction, system and equipment integration and commissioning of the cages
- Detailed engineering, construction, systems and equipment integration and commissioning of the feed platform
- Mooring system design and procurement
- Transportaiton and installation of system offshore

Based on SubFarm engineering and cost estimation and for the purpose of this study, we will assume a unit CAPEX for the offshore fish farming system to be:

- Early production System (3,000 tons): 200 NOK/kg
- Full SubFarm production system (12,000 tons): 90 NOK/kg

6.2.2 Operating costs (OPEX)

As there is currently no established offshore salmon farming industry in Sweden, there is a lack of relevant cost data for estimating the economic potential of such operations.

Therefore, we base our cost estimates on the "Lønnsomhetsundersøkelse for produksjon av laks og regnbueørret 2023" (Profitability Survey for Production of Atlantic Salmon and Rainbow Trout 2023) published by the Norwegian Directorate of Fisheries on November 14, 2024 (archive case number 24/5837, ISSN 2464-4285).

Several factors support the relevance of using Norwegian cost data as a proxy for Swedish offshore salmon farming operations:

- Geographical and socio-economic proximity: The west coast of Sweden and the west coast of Norway share similar climatic and oceanographic conditions, with comparable sea temperatures, wave climates, and salinity levels.

- Economic structure: Sweden and Norway are both highly developed economies with similar salary levels, regulatory standards, and cost structures related to labor, technology, and environmental compliance.

- Aquaculture expertise: Norway's well-established salmon farming industry provides a mature, realistic reference point, whereas Sweden's aquaculture sector is smaller and inland-focused.

- Input markets: Feed, smolt, and equipment suppliers operate on a Nordic or European scale, ensuring that input prices (adjusted for currency exchange) would be similar.

- Technological similarity: Offshore salmon farms in Sweden would likely adopt the same or similar farming technologies as currently used or developed in Norway.

Given these points, the Norwegian 2023 cost structure provides a reasonable and conservative estimate for what can be expected in Sweden.

Table 8 summarizes the average cost components per kilogram of produced salmonid fish in 2023, in both Norwegian kroner (NOK) and converted into euros (EUR) at the April 2025 exchange rate of 1 EUR = 11.7 NOK

Table 8: Estimated Production Costs per kg of Farmed Fish (2023)

Cost Element	NOK/kg	EUR/kg
Smolt cost	6.91	0.59
Feed cost	25.89	2.21
Insurance cost	0.24	0.02
Labor cost	3.78	0.32
Depreciation	0.78	0.07
Other operating costs	20.49	1.75
Net financial costs	2.13	0.18
Production cost subtotal	60.23	5.15
Slaughter and freight	4.45	0.38
Total cost per kg	**64.68**	**5.53**

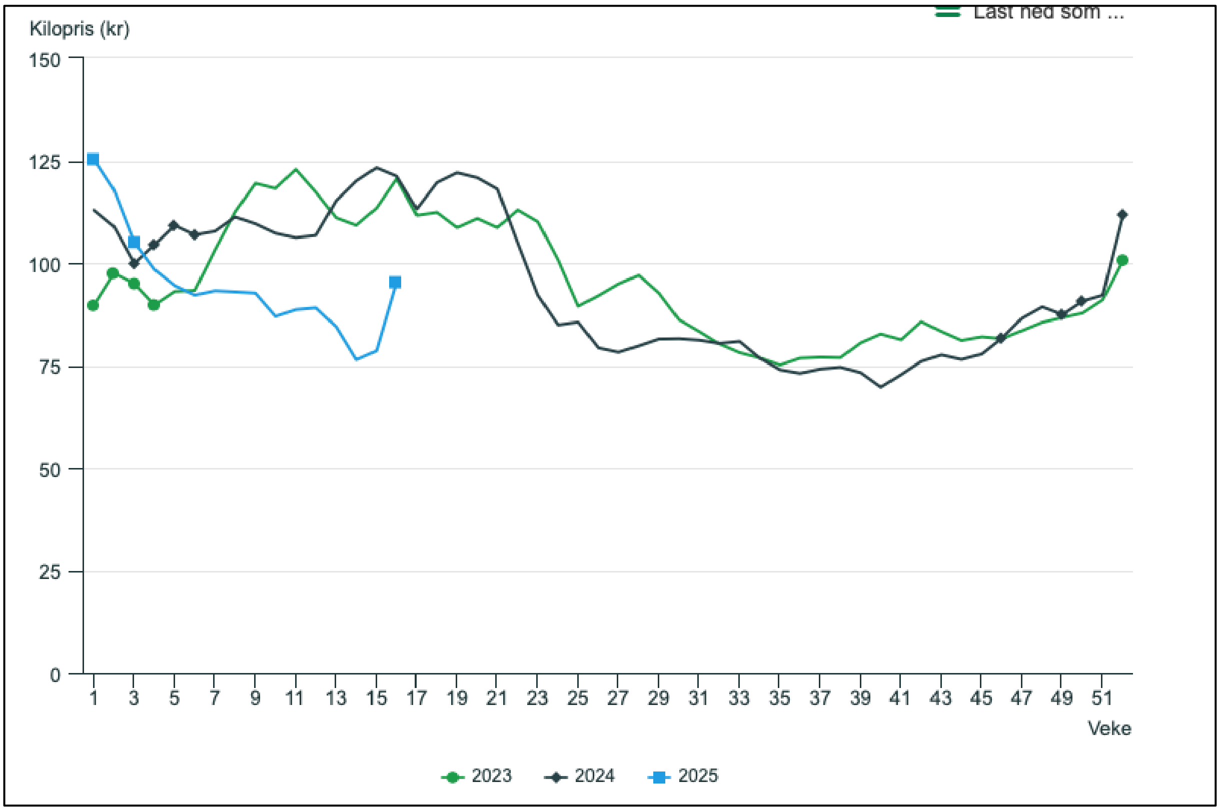
For the purpose of this assessment, we use an operating cost of 65 NOK/kg

6.2.3 Salmon Price

Figure 21 below shows the salmon price (NOK/kg) for export delivered at Norwegian border. This metric is considered relevant benchmark for salmon delivered Swedish west coast.

For the purpose of this assessment, we use 100 NOK/ kg to calculate the revenue from the SubFarm production units at Mareld

Figure 21: Weekly salmon export price for fresh or chilled salmon at Norwegian border (source: Statistics Norway)



6.2.4 Cash flow analysis

In assessing the financial attractiveness of establishing a salmon farm in connection with the Mareld offshore wind farm we have based the calculations on the key assumptions in in Table 9 below.

Table 9: Main assumptions for economic calculations

Project startup-test production	Jan-26	
Project startup-full farming	Jan-28	
System Capacity	51 000	tons/yr
Smolt Size	250	g
Transport, smolt	12	NOK/smolt (when need for import)
Mortality	10%	from hatch to slaughter
OPEX (incl smolt and slaughter)	65,00	NOK/kg (HOG)
Sales price	100,00	NOK/kg (HOG)
CAPEX (ex upgrades and hatchery)	4 700	Mill NOK

It is assumed that smolt (fingerlings) is imported from Norway in an initial phase, until sufficient hatching capacity is developed locally. First smolt from local hatchery is assumed in 2031.

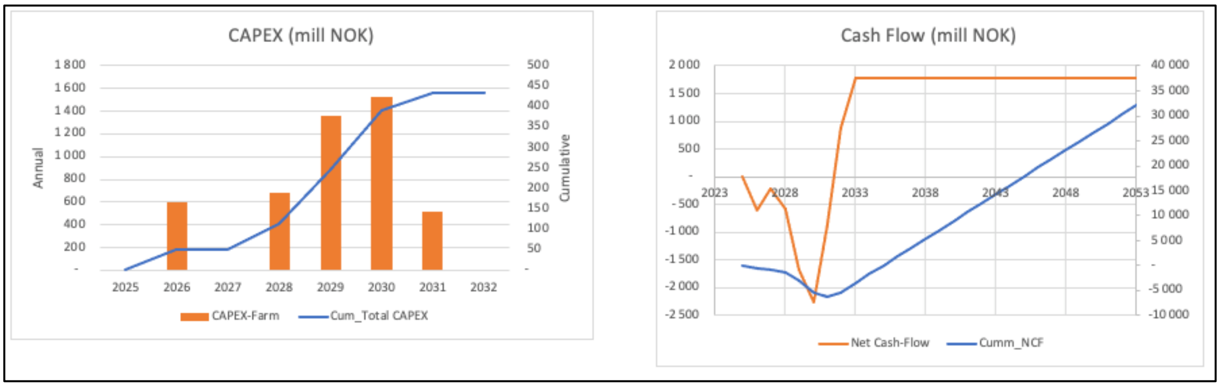
Economics are calculated on a pre-tax basis and includes the offshore farming cash flow only. All costs for smolt, feed and services are included in the operating costs.

The economic performance yardsticks of the farming investment project are listed in Table 10 below, and illustrated in graphs in Figure 22.

Table 10: Key economic performance yardsticks

Annual Net Cash Flow (before tax	1 800	mill NOK
Total Net Cash Flow (before tax)	40 860	mill NOK
NPV 10% (disc. to 1/1/25)	4 204	mill NOK
IRR (return on total capital)	19%	
Pay-back period	9	years

Figure 22: CAPEX and Cash flow from the Mareld salmon fish farm project



Based on the assumptions provided in Table 2 and the performance indicators in Table 3, the proposed offshore salmon farming project appears to be economically attractive, albeit with a moderately long payback period:

- Annual and Total Net Cash Flow (before tax) are estimated at NOK 1.8 billion and 40.86 billion, respectively, indicating a strong long-term revenue potential from the operation.

- Net Present Value (NPV) at a 10% discount rate is NOK 4.2 billion as of January 1, 2025. A positive and substantial NPV suggests the project is expected to generate value above the cost of capital, making it financially viable.

- Internal Rate of Return (IRR) is 19%, well above typical investment hurdle rates (often around 10–12% for infrastructure or aquaculture projects), which signals a robust return on invested capital

- Payback Period is 9 years, which is relatively long but acceptable for large-scale infrastructure or aquaculture investments with high upfront capital expenditure (CAPEX of NOK 4.7 billion)

- The assumed mortality rate of 10% is within industry norms, supporting the biological feasibility of the offshore farming concept

In summary, this offshore salmon farming initiative represents an attractive investment opportunity with high expected returns (19% IRR) and strong cash flow generation (NOK 40.9 billion), although investors must be prepared for a longer payback period of 9 years and significant upfront capital requirements. The project's strategic integration with renewable energy infrastructure further enhances its profile as a forward-looking and sustainable venture.

6.3 Case study: The Economic Impact of Fish Farming in Rogaland and Potential Impact on the Swedish West Coast

6.3.1 Introduction

This chapter aims to analyse the potential for value creation from offshore fish farming on the Swedish west coast. To provide a benchmark, the chapter uses Rogaland in Norway as a case example, based on its established aquaculture sector and well-documented economic impacts. The comparison aims to estimate the direct and indirect economic benefits Sweden could achieve by developing a similar offshore fish farming industry.

Rogaland is a relevant benchmark for several reasons:

- Biological and Environmental Conditions: Both Rogaland and the Swedish west coast share similar marine environments, characterized by fjord-like coastlines and exposure to the North Sea. These conditions are conducive to offshore aquaculture development (Swedish West Coast Marine Environment Overview, diva-portal.org).

- Water Temperature Ranges: The sea temperatures in Rogaland range between 5°C and 15°C throughout the year, comparable to those along the Swedish west coast. Such temperatures are suitable for farming species like Atlantic salmon and rainbow trout (diva-portal.org).

- Production Volumes: In 2023, Rogaland produced approximately 106,401 metric tons of Atlantic salmon and 952 metric tons of rainbow trout (Fiskeridirektoratet, 2024).

By examining Rogaland's aquaculture sector, this chapter seeks to provide insights into the economic opportunities and considerations for developing offshore fish farming in Sweden.

6.3.2 Direct and Indirect Economic Impact in Rogaland (2022)

1) Value Creation
   - Total value creation: NOK 2.33 billion.
   - Direct value creation (core activities): NOK 1.38 billion.
   - Indirect value creation (ripple effects): NOK 0.95 billion.

2) Employment
   - Total employment: ~1,700 persons.
   - Direct employment (core activities): ~700 persons.
   - Indirect employment (ripple effects): ~1,000 persons.

3) Sector Structure

The Rogaland seafood industry is characterized by a strong aquaculture sector, mainly focused on salmon and trout farming, complemented by wild fish landings. Significant ripple effects are observed through supplier industries such as feed production, logistics, transport, and technical services. Key municipalities include Stavanger, Hjelmeland, and Eigersund (Nofima, 2024).

Sources: Nofima Report 32/2023, figures 23, 49, and 50

6.3.3 Potential Economic Impact of Offshore Fish Farming on the Swedish West Coast

Assuming that offshore salmon and trout farming along the Swedish west coast could reach a production volume similar to Rogaland (approximately 107,000 tons), a reasonable projection of value creation and employment can be made.

1) Estimated Value Creation
    - Direct value creation: SEK 1.4–1.6 billion.
    - Indirect value creation: SEK 1.0–1.2 billion.
    - Total value creation: SEK 2.4–2.8 billion.
2) Estimated Employment
    - Direct employment: 700–800 persons.
    - Indirect employment: 1,000–1,200 persons.
    - Total employment: 1,700–2,000 persons.

These estimates assume similar production structure, labor intensity, and supply chain maturity. They could increase if Sweden invests in domestic supplier industries and processing facilities.

Key Considerations for Sweden

- Supplier Industry Development: Establishing a robust local supplier base would increase ripple effects domestically.
- Infrastructure Needs: New offshore farming infrastructure, harbors, and service vessels would be required.
- Market Access: Close proximity to EU markets offers advantages in logistics and trade.
- Regulatory Framework: Sweden needs to develop regulations for offshore aquaculture.

6.3.4 Conclusion

Using Rogaland as a benchmark illustrates that a regional aquaculture cluster producing 107,000 tons of salmon and trout can generate NOK 2.33 billion (SEK ~2.5 billion) in value creation and approximately 1,700 jobs. If the Swedish west coast were opened for offshore salmonid farming and developed to similar scale, comparable regional economic effects could be expected. Strategic policy design and investment in infrastructure and supply chains would be key to unlocking this potential.

6.4 Conclusion

Overall, the financial projections support the case for investment in offshore salmon farming as a viable and profitable venture on the Swedish west coast.

These figures, combined with a case comparison with the region of Rogaland in Norway, indicate that offshore aquaculture could become a cornerstone of a new industrial sector in the region, with ripple effects across logistics, technology, and services. However, realizing this potential depends on strategic investments in infrastructure, supply chains, and regulatory frameworks.

The Mareld offshore fish farming project presents a compelling investment opportunity, combining high profitability with the potential to anchor a transformative regional industry. If managed strategically, it can deliver strong returns for investors while driving meaningful economic development along the Swedish west coast.

7. OVERALL CONCLUSION

This report has documented the results of SUBFARM AS's work in the OFFWOFF project, focusing on the technical, operational, biological, and economic feasibility of co-locating submerged fish farms within the Mareld offshore wind farm. Drawing on detailed assessments across engineering, logistics, environmental conditions, stakeholder interests, and business potential, the findings support the conclusion that offshore aquaculture and floating wind energy can successfully coexist in the Mareld area—provided that implementation is guided by sound planning and adaptive management.

The SubFarm concept is technically mature and well suited for integration within large-scale offshore energy projects. Operational synergies can be achieved in logistics, inspection routines, and land-based infrastructure. From a biological perspective, the Mareld site appears largely suitable for salmon farming, although further site-specific measurements of water current duration and oxygen levels at depth are recommended to ensure full biological confidence.

Stakeholder analysis and economic modeling indicate strong potential for regional value creation and green industrial development. If realized, the proposed co-location project could serve as a model for future marine multi-use zones in Sweden and the wider Nordic region.

Taken together, the results presented in this report form a robust foundation for moving the Mareld co-location concept from feasibility assessment toward phased implementation. The next steps should include site-specific environmental data acquisition, permitting pathway clarification, stakeholder engagement, and pilot-scale deployment. With these elements in place, Mareld could become a flagship for integrated, sustainable use of offshore marine space.

8. REFERENCES

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