Offshore Low-trophic Aquaculture in Multi-Use Scenario Realisation

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Executive Summary
The OLAMUR project aims to demonstrate the potential of multi-use activities in three pilot farms located in Germany, Denmark, and Estonia. While there are similarities in the technology and system design, each site has specific tasks based on local conditions, stakeholders, and market. Experienced partners will lead each case study, working with their partners to identify the optimal multi-use site, secure permits, discuss logistical issues, and evaluate and iterate on these aspects during the second grow-out year. The foundation of the project is WP1, with a focus on cooperation among multi-use partners, and data generated from other WPs is fed back to WP1. Task D1.1 is dedicated to identifying the optimal multi-use site, securing permits for LTA, discussing logistical issues, and evaluating and iterating on these aspects during the 2nd grow-out year. WP1 is a foundation for the entire OLAMUR research project, and its activities serve as a basis for the following WPs. Special emphasis is placed on cooperation among multi-use partners, and data is generated and fed back to WP1 from other WPs.

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Overview:

Deliverable 1.1 of the OLAMUR project seeks to produce a “Document on identifying optimal spaces for OLAMUR Multi-use Pilot Farms: site-selection, permits, and logistics”. The OLAMUR research project focuses on demonstrating the feasibility and potential benefits of multi-use activities in the marine environment. To achieve this goal, the project has selected three pilot farms (Case Studies) located in promising sites of the North Sea (Germany) and the Baltic Sea (Denmark and Estonia). These Case Studies are planned in different water basins and have different access conditions, but they share similarities in technology and system design, low trophic aquaculture (LTA) candidate selection, and operation and maintenance strategies.

The activities related to the planning (organization) of multi-use scenarios are summarized in Part I and realized in tasks 1.1-1.3. All other activities related to the construction and operation & maintenance of the LTAs are contained in Part II (tasks 1.3-1.5).

Task 1.1 focuses on identifying the optimal multi-use site in the area off or next to the host partner by using and evaluating all necessary data to set up the LTA farm (Case Study sites A-C). Site-selection criteria are gathered, evaluated, summarized in a criteria catalogue and provided for tasks 1.2 and 1.3. Permits for LTA in selected sites will be secured in dialogue with national authorities, and all logistical issues for the realization of the LTA farm in the test area will be discussed. The logistical aspects are evaluated and iterated during the 2nd grow-out year (logistics II).

Hydrodynamics:

Includes site flow rate, turbulence, and depth. Proper hydrodynamics ensures that the water quality remains optimal for aquatic species, as it facilitates the circulation of oxygen and nutrients and prevents the build-up of waste products. Factors to consider when evaluating hydrodynamics for aquaculture include the location and intensity of currents, tides, and waves, as well as the topography and physical characteristics of the site's water column. A thorough understanding of hydrodynamics improves the overall productivity and sustainability of the aquaculture operation.

Hydrodynamics also influence the safety of operation of working vessels and related activities in the area, as strong currents and waves can limit the effective working days in the area and compromise safety of infrastructure and personnel.

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Seabed:

Refers to the bottom of the ocean or other bodies of water and its composition, including the type of sediment, depth, and bathymetry. The suitability of the seabed for aquaculture will depend on factors such as water depth, currents, wave action, and the presence of any obstacles or hazards. The seabed composition also affects the stability of anchoring of the cultivation structures. A suitable seabed is essential for providing a stable and secure environment for aquaculture operations, as well as supporting healthy and productive aquatic ecosystems.

Synergies:

The co-location of multiple uses in the same marine space can lead to efficient resource utilization, reduced environmental impacts, and enhanced ecosystem services. However, realizing potential synergies requires careful planning and management. It is important to recognize the benefits of potential synergies and work towards their implementation. To achieve any benefit an understanding of the ecological and physiological interactions between different species involved as well as knowledge of how different commercial operations engage with one another is required.

Licensing:

The process of obtaining licenses and permits for aquaculture operations can be complex and requires coordination with both local and national regulatory authorities. These authorities are responsible for ensuring that aquaculture operations are conducted safely and sustainably, with minimal impact on the environment and surrounding communities.

At the local level, regulatory authorities may include city or municipal governments, as well as regional or state environmental agencies. These authorities may be responsible for approving site-specific environmental assessments, issuing permits for water use, and conducting inspections to ensure compliance.

At the national level, regulatory authorities may include federal environmental agencies. These agencies may be responsible for issuing licenses and permits for aquaculture operations, conducting environmental impact assessments, and monitoring compliance with national environmental standards.

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Logistics:

Logistics is an important to consider when selecting a site for aquaculture. It refers to the planning, coordination, and management of the flow of goods, services, and information between the producer and the consumer. This involves the transportation of fish, macroalgae crop, feed, equipment, and personnel to and from the site, as well as the maintenance of aquaculture structures, and management of waste and by-products.

When selecting a site, it is important to consider the logistical challenges that may arise, such as access to transportation infrastructure, proximity to markets, and availability of skilled labour. Factors such as the distance to processing facilities, shipping ports, and major transportation routes can have a significant impact on the efficiency and cost-effectiveness of aquaculture operations.

In addition to these considerations, plans for the management of waste and by-products generated by the operation are needed. This may involve developing systems for the collection, treatment, and disposal of effluent and solid waste, as well as identifying opportunities for the reuse or recycling of these materials.

Site A: Low trophic aquaculture system within the Meerwind Süd/Ost OWF

Purpose of LTA site:

In the German case study, different LTA species are considered for multi-use by open ocean aquaculture within the OWF site: (1) macroalgae, such as sea lettuce (*Ulva spp.*) and sugar kelp (*Saccharina latissima*), and (2) bivalves, such as mussels (*Mytilus edulis*) and the European oyster (*Ostrea edulis*). All these candidates have different requirements for the place of cultivation. While the macroalgae need sunlight and therefore do not have to be positioned far below the water surface, the mussels can be cultivated in a submerged, and thus somewhat more protected, mode. This means that the technologies are different, namely the so-called Shellfish Tower (Heasman et al. 2021, Landmann et al. 2021) for cultivating oysters and macroalgae and a smart farm concept for cultivating mussels. The selection of parameters and criteria was based on the offshore site selection criteria catalogue by Buck & Grote (2018).

Proposed cultivation site – Part I (estimate):

Corner	Position East	Position N
A	7° 7.75944	54° 23.360400
B	7° 45.130200	54° 23.360400
C	7° 7.75944	54° 23.398800
D	7° 45.130200	54° 23.398800

Table A1. Positions of the corners of the cultivation area given in DATUM WGS84 Part I (estimate).

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Proposed cultivation site – Part II (estimate):

Corner	Position East	Position N
A	7° 45.568800	54° 24.425400
B	7° 45.306600	54° 24.273000
C	7° 45.262800	54° 24.451200
D	7° 45.568800	54° 24.258600

Table A2. Positions of the corners of the cultivation area given in DATUM WGS84 Part II (estimate).

Currently, there are two proposals for the positioning of the LTA-MU scenario in the OWF Meerwind Süd/Ost. Criteria for this selection were the physical-ozenographic data (currents and waves in all their facets, temperature, salinity), topographic data (seabed, bottom conditions, depth at low tide), biological data (nutrients, plakton availability) and data obtained in the local site selection criteria analysis, that could be of importance to the cooperation with the synergy partner (sharing of vessel time and personnel, observation and controls, sampling) and finally data on safety (vessel suitability, entry and navigation concepts, level of training, distance to foundations, safety zones and underwater power grid).

Not all data could be fully identified so far. Therefore, two areas are currently proposed for multi-use. The final selection of one of these two areas will be made together with the approval authority. This process is still ongoing - AWI has submitted an application to the BSH (Bundesamt für Seeschifffahrt und Hydrographie – Hamburg/Germany [Federal Maritime and Hydrographic Agency]).

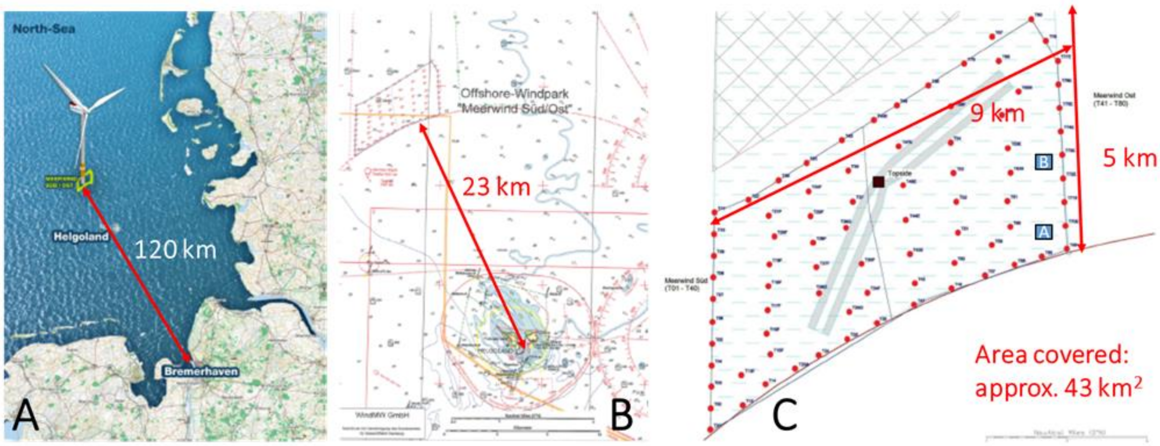

Figure A1. Site and layout of the OWF Meerwind Süd Ost. A: Distance of the OWF to Bremerhaven; B: Distance of the OWF to the island of Helgoland; C: Layout and size of the OWF and positions of the foundations. Positions A and B are potential multi-use sites.

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Hydrodynamics:

The data used here was provided by our partner WindMW and is based on the report WindMW (2010). The hydrodynamics in the area are as follows: the tidal current natural to the German North Sea coast (net counterclockwise flow from the Netherlands in the southwest along the German coastal sea to Denmark in the northeast) is slightly different at the Case Study site and follows a towards the West and the East (depending on the tide). Current velocities are 0.56-0.64 m/s at maximum (0.30-0.32 m/s on average). More detailed data are as follows:

Return period [years]	Depth-averaged current speed [m/sec]	Near-bed current speed [m/sec]	Surface current speed [m/sec]	Depth-averaged current direction [°]
1	0,58	0,32	0,79	290
10	0,62	0,34	0,89	290
50	0,67	0,36	0,93	270
100	0,70	0,38	0,96	270

Table A3: The tidal range can be estimated at about 2.5 m.

Return period	Significant wave height	Significant wave height 90 % confidence level
Jahre	[m]	[m]
1	6,95	6,55 – 7,25
2	7,59	7,29 – 7,89
5	8,61	8,34 – 8,88
10	9,09	8,80 – 9,38
50	9,78	9,29 – 10,27
100	9,97	9,42 – 10,52

Table A4: The significant wave height for certain return periods.

Seabed:

This is a sandy bottom structure. This is well suited for the technology used, as it allows the installation or placement of different types of anchors (drill anchors, Danforth anchors or similar). Stony or rocky seabed does not allow such anchorages for the chosen farm technologies. Likewise, stony and rocky bottom can damage the mussel farm when submerging into deeper water layers or the placement on the seabed (e.g., during storm events) and thus lead to abrasion of the mussels.

Synergies:

Previous synergies are more or less reduced to tolerating research projects in the area of the wind farm and taking over surveillance tasks. The category of this form of multi-use would be type 4 (Schupp et al. 2019). Future synergies include the sharing of vessels, personnel, surveillance and operations and maintenance.

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Licensing:

This process is still ongoing - AWI has submitted an application to the BSH (Bundesamt für Seeschifffahrt und Hydrographie – Hamburg/Germany [Federal Maritime and Hydrographic Agency]) in June 2023. As there have been no such applications to date (multi-use of an open ocean aquaculture within an OWF), the BSH first had to consider the legal basis on which such a project could be examined and possibly approved. Therefore, there was a lively exchange of discussions and a presentation by the AWI for the BSH. Currently, the entire system was applied for as a "closed" measuring point, as this is a common procedure and all components (including the mooring) can be covered in this way.

Logistics:

The location of the German case study is far away: 120 km from Bremerhaven (mainland) and about 24 km from the offshore island of Helgoland. The farm's service is managed from Helgoland, as there are logistical advantages there. The service of the test facility can be carried out with the vessels and personnel of the AWI and the wind farm operator WindMW. Both partners have a facility on Helgoland, AWI has a field station with about 80 employees, WindMW has the service boat and all logistics for the OWF Meerwind Süd-Ost there. As potential customers for aquaculture products, tourism on the island is also a good source of customers. However, all logistical planning can only begin when the installation is set up, moored and operated. In the case of the German scenario, this will not take place until the beginning of 2024.

Site B: Low trophic aquaculture system within the Danish Kriegers Flak wind farm

Purpose of LTA site:

In the Danish Kriegers Flak (DKF) windfarm, a pilot-scale production system will be licensed, deployed, and operated for two cultivation seasons. This initiative aims to cultivate at least three native species of seaweeds (sugar kelp, sea lettuce, and dulse) and blue mussels. The project's objectives include assessing the production potential of these species in high-energy, low-saline conditions, evaluating their nutrient and carbon uptake capabilities, ensuring food safety of the cultivated species in the Baltic, harmonizing risk assessment procedures for multi-use between the wind farm and the pilot system, optimizing operational synergy between the wind farm and the LTA (Long-Term Adaptation) farmer, and integrating marine monitoring of environmental parameters into the Danish Marine Monitoring Program with a focus on data quality and spatial resolution.

Proposed cultivation site:

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The size of the cultivation area will be 750*250 m, equivalent to 18.75 hectares. The location is in the southwestern part of the DKF with nearest monopiles being #17, #18, #20 and #21 (Figure B1). Non-project related traffic should be avoided in the area.

The cultivation site will be marked with corner buoys as per recommendations from the Danish Maritime Authorities, the specifications are still being negotiated, but plans are to deploy three types of buoys, two of each type, in order to gain more knowledge on what types would be best suited for the purpose, while still meeting the budget of a potential future sea farmer. The corner positions of the entire area are given in Table B1.

Within the area, four mainlines of each 200 m, will be anchored to the seabed using drill anchors (figure B2). The lines will be connected in series.

Corner	Position East	Position N
A	012° 47.192' E	54° 58.634' N
B	012° 47.716' E	54° 58.904' N
C	012° 47.872' E	54° 58.803' N
D	012° 47.348' E	54° 58.534' N

Table B1. Positions of the corners of the cultivation area given in DATUM WGS84

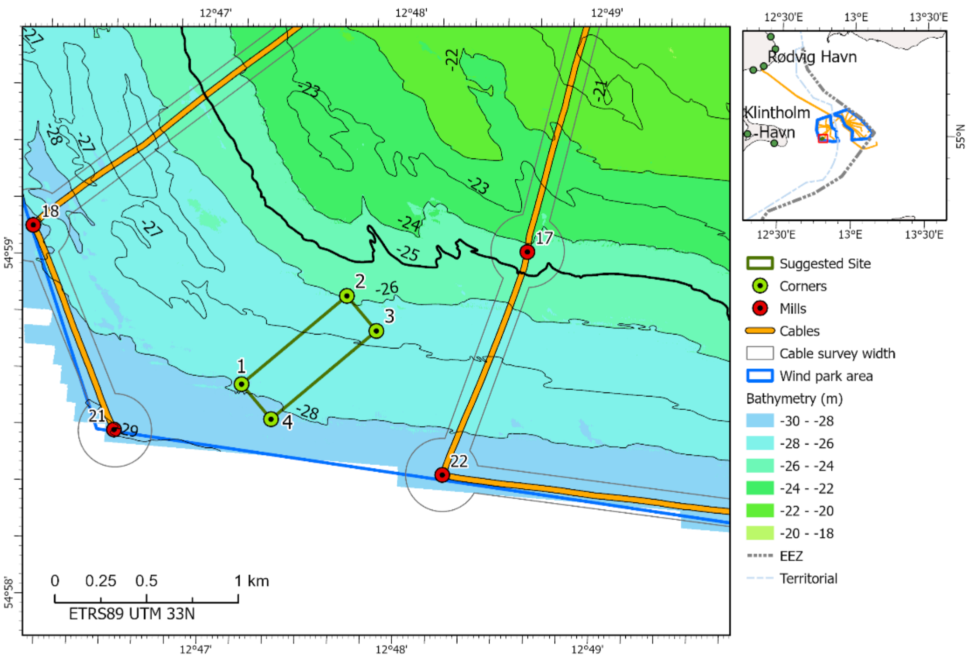

Figure B1. Location of the low trophic aquaculture structure at Danish Kriegers Flak, with indication of seabed topography, monopiles and cables in the area.

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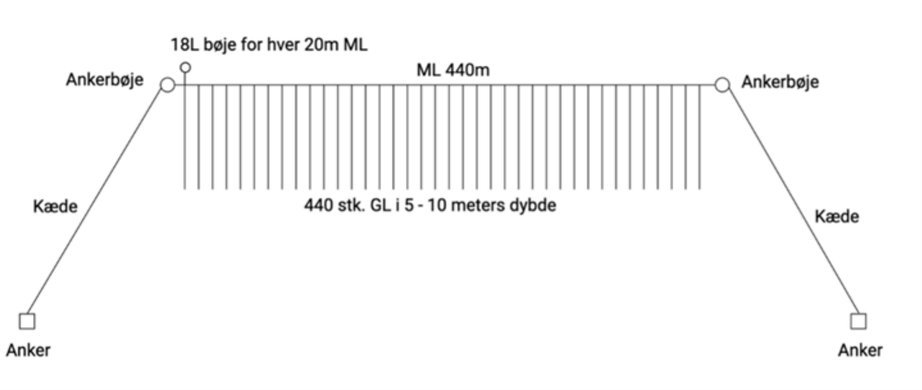

Figure B2. The design of one of the four mainlines to be deployed at DKF.

Hydrodynamics:

The hydrodynamics in the area are dominated by weak currents (reaching up to 1 m/s or 0.5 kn) from all directions except from SE. The dominant depth averaged currents are SW currents, whereas the strongest currents in the area typically come from NE (Figure B3). Thus, the cultivation area and the cultivation lines will be positioned in parallel with both the dominating and the strongest currents.

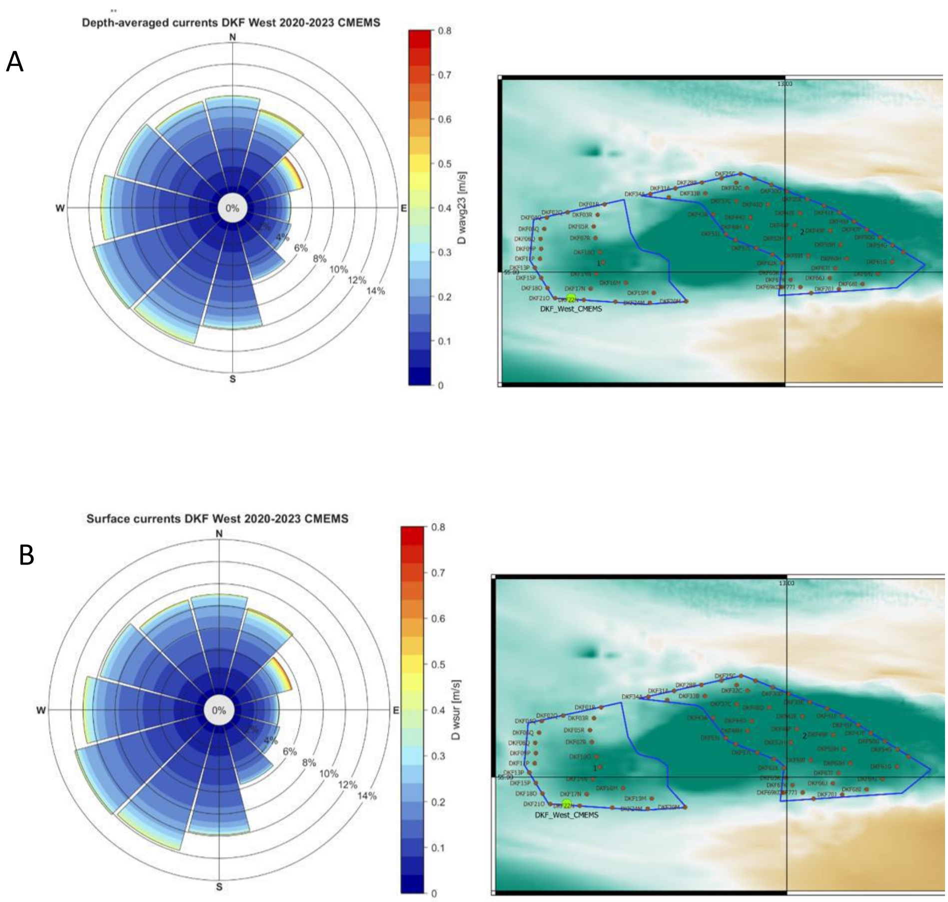

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Figure B3. A) Depth averaged and B) surface currents at DKF, with suggested cultivation site marked with green. Dominant currents from SW and strongest currents from NE – both parallel to suggested orientation of cultivation lines (Data supplied from Vattenfall).

Seabed:

The seabed at the site is predominantly sand, with a softly sloping seabed. The depth in the cultivation area ranges from 26 m in the NE corner to 28 m in the SW corner.

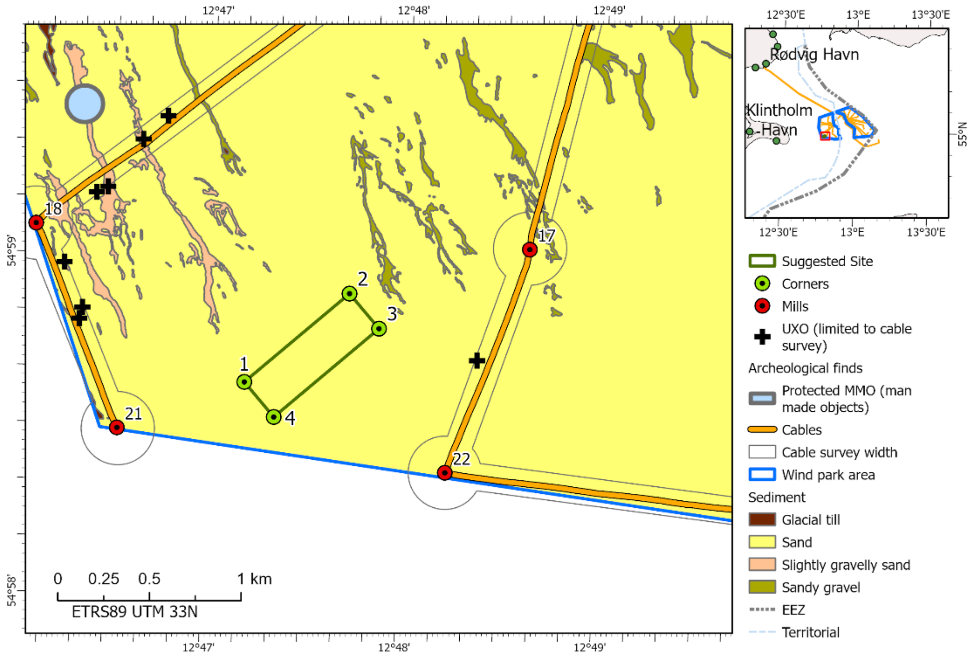

Figure B4. Sediment characteristics in the southwestern DKF. Cultivation area marked with green line is located in area with sand (Data supplied from Vattenfall).

Synergies:

In the proposed site for multi-use, several synergies are expected to be obtained. The crew of the DKF Crew Transfer Vessel (CTV), which operates in the area on a daily basis, will conduct visual inspections of the cultivation structures, lines, and buoys. They will report their observations to Kerteminde Seafarm and the OLAMUR site leader on a weekly basis, following procedures that have been described and accepted by Vattenfall. The CTV crew will also engage in monthly monitoring of environmental parameters by taking CTD measurements and water samples for water chemistry analysis while waiting for service crew in the wind farm. Additionally, the CTV crew will exchange elements of monitoring buoys/cameras during specific operations. The CTV vessel's presence in the area offers potential assistance in case of technical problems for the cultivation boat at the site, and it may also support the decommissioning of the cultivation system.

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Licensing:

Permits for seaweed cultivation in Danish waters is granted by the Danish Coastal Authorities, whereas the permit for bivalve cultivation is granted from the Danish Fisheries Authorities. Since DKF is not presently identified as a 'shellfish aquaculture zone' in the Danish Maritime Spatial Plan, we need a dispensation from the Danish Maritime Authorities for the bivalve cultivation prior to sending in an application for licence to the Fisheries Authorities. At present, the seaweed cultivation licence for DKF is expected to go through in June/July 2023, whereas the bivalve licence application awaits green light from the Danish Maritime Authorities.

Logistics:

The successful operation of the site requires several types of specific operations. In late August 2023, several operations will be carried out to establish and maintain the ULTFARMS cultivation system. Marker buoys will be deployed and drill anchors will be established, requiring the chartering of a large vessel through FOGA, which is commonly chartered by Vattenfall. The Swedish company Carapax will be specifically chartered for their expertise in the establishment of drill anchors. To optimize logistics and budgets, this operation will coincide with the establishment of the ULTFARMS cultivation system. FOGA will also be responsible for the annual maintenance of the corner buoys of the farm. Kerteminde Seaweed, utilizing their large vessel, will handle the establishment and decommissioning of the seaweed/mussel cultivation system. The vessel will be sailed from Kerteminde to DKF for the system's establishment and subsequent decommissioning at the end of the second cultivation season. Kerteminde Seafarm will be responsible for the deployment of seaweed lines, mussel spat collectors, and the monitoring and maintenance operations within the farm, utilizing their smaller designated vessel. Additionally, the daily visual inspection of the seaweed/mussel farm will be conducted by the Vattenfall CTV crew, as described under the 'synergies' section.

In an off-shore exposed environment as at DKF, we expect a limited number of suitable working days at sea, due to challenging wind and sea conditions. This is to some extent mitigated by the daily/weekly visual inspection from the CVT crew, as this will free Kerteminde Seafarm from being present in the farm every day/week. By using the Kerteminde Seafarm vessel for the planned monitoring and maintenance operations, will on the other hand avoid conflicts of interest, as on days with good working conditions at sea, the CTV will be fully used by Vattenfall/Siemens.

Other Considerations:

One of the factors in the selection of the area, is the traffic intensity, which is at its lowest in the wind farm in this particular area (Figure B4). Another important consideration is the salinity at DKF, which is low (<10 psu). This will propose a known challenge for the cultivation and production potential of both the seaweed (in particular the *Saccharina latissim*a) and the bivalves at DKF. The challenge will be addressed by using local ecotypes of the seaweeds to be cultivated, expecting an adaptation to the local environment and lower salinity. It is known from biological surveys in the area, that blue mussels grow naturally in the area, and we expect natural settling of mussel spat on our systems. Testing the limits of cultivation conditions, this

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cultivation will give valuable inputs to the modelling in WP2, for defining optimal locations and site-selecting tools for seaweeds and bivalves in wind farms.

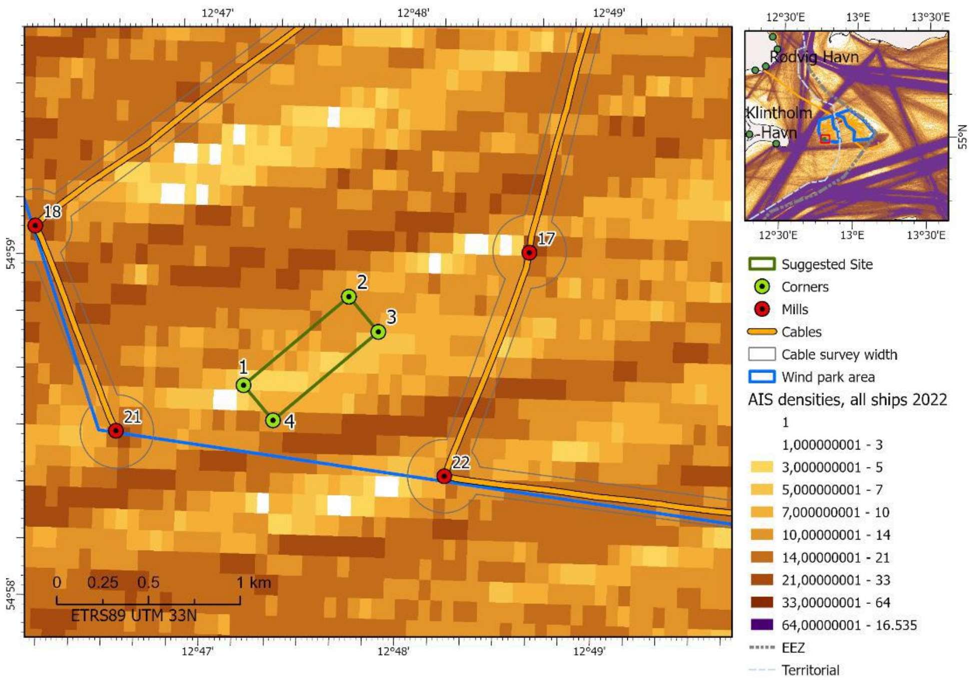

Figure B5. Traffic intensity (ship density) in the DKF area. Suggested cultivation area marked with green line (Data from the Danish Maritime Authorities).

Site C: Low trophic aquaculture system within Estonian open water and land based fish farms

Purpose of LTA site:

Producing healthy food in an environmentally friendly manner represents one of the largest global challenges. Per capita fish consumption has more than doubled since the 1960s, and natural fish stocks are no longer able to satisfy this increased demand. Therefore, aquaculture holds significant potential to meet the growing need for fish and other seafood products. Today, over half of all fish consumed worldwide are produced under artificial conditions (FAO, 2020). Although aquaculture is the fastest-growing food sector globally, it constitutes a relatively small industry in Estonia. However, interest in developing Estonian fisheries and aquaculture is steadily increasing.

In 2014, the European Commission adopted a reform of the Common Fisheries Policy to promote, among other things, the development of aquaculture. This document encompasses strategic guidelines for sustainable aquaculture development, aligning with EU common priorities and overall objectives. Four areas are considered priorities: reducing bureaucracy, improving access to land and water, enhancing competitiveness, and leveraging competitive

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advantages through strict quality, health, and environmental standards. Consequently, the focus should be on ensuring that production is sustainable and high quality, guaranteeing food safety for consumers.

At present, nutrient levels in the Baltic Sea are excessively high, making it necessary to limit the input of nitrogen and phosphorus compounds into the sea in order to improve water quality. This excess nutrient influx leads to uncontrolled proliferation of microalgae in the water column, massive growth of filamentous macroalgae on the seafloor, reduction of water clarity, excessive sedimentation of organic matter, oxygen deficiency in the near-bottom water layers, and the consequent decline of more sensitive aquatic organisms (Kotta et al., 2017).

In the open aquaculture systems at Tagalaht Fish Farm (Figure C1), fish are raised in net pens. Traditional open net pen farming is a cost effective and proven method that requires less equipment than other farming techniques. However, open net pens are in direct contact with the surrounding ecosystem and therefore pose a higher risk of environmental impact than closed production systems. Nutrients that escape from the farm come from fish faeces and feed residues, which can be present in dissolved form or settle on the seabed. In addition, fish excrete nitrogen and phosphorus into the marine environment through their gills and urine. Given the potential contribution of fish farming to environmental problems such as eutrophication, it would be reasonable to favour nutrient-neutral or nutrient-extractive aquaculture under the eutrophic conditions of the Baltic Sea.

Orthophosphates (mineral forms of phosphorus compounds) and dissolved nitrogen compounds released from fish farms are readily available to planktonic organisms in the water column. Excessive levels of dissolved nutrients in seawater can lead to symptoms of eutrophication, including algal blooms, so it is sensible to implement compensatory measures to remove nutrients released into the water column and prevent undesirable environmental impacts. One such strategy is the establishment of mussel farms, which have the potential to remove excess nutrients from seawater. The mussels in these farms filter significant amounts of phytoplankton, and thus remove phosphorus and nitrogen, from the seawater.

An industrial shellfish farm has been established in Tagalaht to offset the negative environmental impact of fish farming. A recent study described the yield of the shellfish farm in this area, its potential for nutrient removal, and the direct effect of shellfish farming on the nutrient balance in the water column. The study revealed that the positive environmental impact of shellfish is significantly greater than merely the amount of nutrients deposited in the shellfish themselves. Thus, shellfish farms should be regarded as biogenic filters, enhancing the environment even when shellfish are not removed from the farm (Kotta et al., 2023).

In Estonia, including in the case of the Tagalaht Fish Farm, aquaculture establishments (Figure C2) are required to adhere to a stringent licensing process to ensure the ecological sustainability and public health safety of their operations. The process involves multiple stages, starting with the submission of a detailed plan outlining the proposed farm's structure, species to be cultivated, methods of cultivation, and measures to mitigate environmental impact. This plan is then evaluated by a host of regulatory bodies, including the Ministry of Environment and the Ministry of Rural Affairs. The licensing process also includes a public

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consultation period and an environmental impact assessment. The licensing requirements are designed to ensure the operation aligns with both national and European Union regulations regarding biodiversity, water quality, and food safety, amongst other factors.

Proposed cultivation site (Tagalaht Bay):

Corner	**Position East**	**Position N**
A	22.06219	58.46800
B	22.09420	58.46800
C	22.09420	58.45224
D	22.06219	58.45224

Table C1. Positions of the corners of the cultivation area given in DATUM WGS84

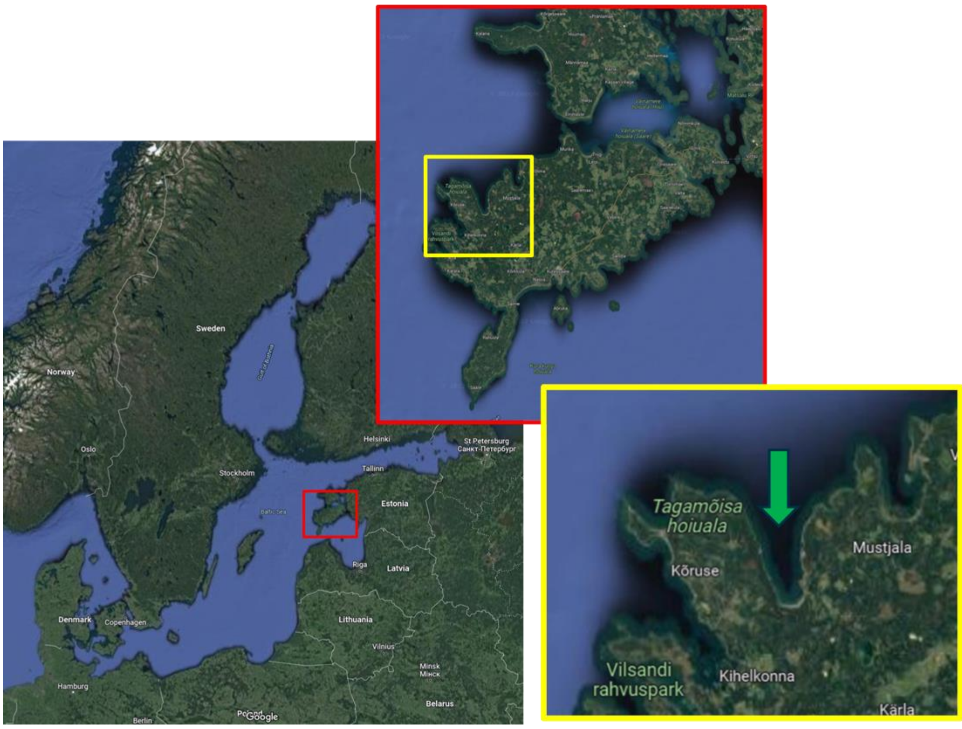

Figure C1. Location of the aquaculture site, Tagalaht Fish Farm, Tagalaht Bay, Saaremaa Island (Redstorm OÜ).

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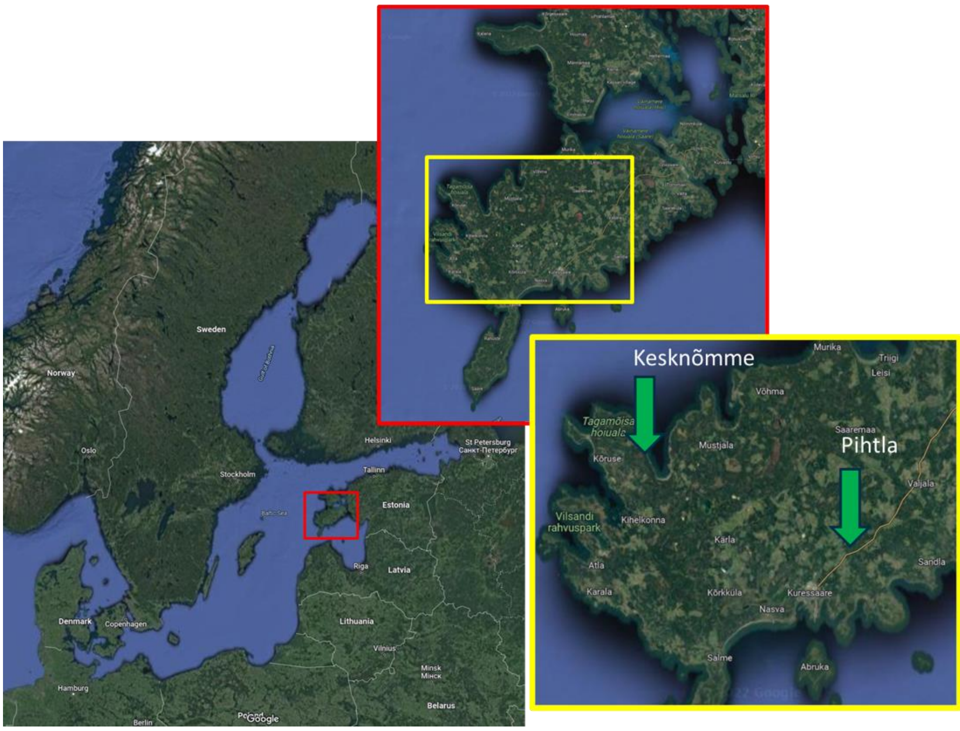

Figure C2. Location of onland fish farm and experimental *Ulva* incubation sites at Kesknõmme fishfarm, Tagalaht Bay and Pihtla fishfarm, Saaremaa island (Ösel Aquafarms OÜ).

Hydrodynamics:

The hydrodynamic characteristics of Tagalaht Bay offer unique opportunities and challenges for both mussel and finfish farming. The area is known for its low salinity (Figure C3) and this is why mussels in Tagalaht Bay tend to reach smaller maximum sizes than their counterparts in areas with higher salinity. However, this limitation is compensated by the high phytoplankton biomass in the area, which can increase the growth rate of mussels in the early stages of their growth. In addition, the density of small mussels is very high in such farms.

Tagalaht Mussel Farm is self-regulating since the farming relies on recruitment of free-swimming larvae from wild populations that disperse passively from natural mussel reefs. After dispersal, larvae attach themselves to farm substrates. Our test farm uses a smart farm system, i.e., mussels are grown on nets placed at 1-5 m depth and attached to long buoyancy lines. Mussels are cleaned and harvested by specialized machines, which run along the nets. The mussel farm has an area of 0.25 hectares and consists of six 100 m long farm lines. The stocking density of such mussel farm is approximately forty million individuals (Kotta et al., 2020). The cultivation period is from the 1st of June to the 31st of October of the following year, i.e., the biomass is harvested 1.5 years after the establishment of the farm.

On the other hand, Tagalaht Bay are particularly suitable for finfish farming. The water movement patterns ensure adequate oxygenation and nutrient cycling, which are essential for the health and growth of finfish. In addition, the semi-enclosed nature of the bay provides a degree of protection from extreme weather conditions and water fluctuations (Figure, C7), which can be beneficial in maintaining stable farming conditions. In addition, the water temperature and salinity levels in the area are conducive to the growth (Figure C3, C5, C6, C8).

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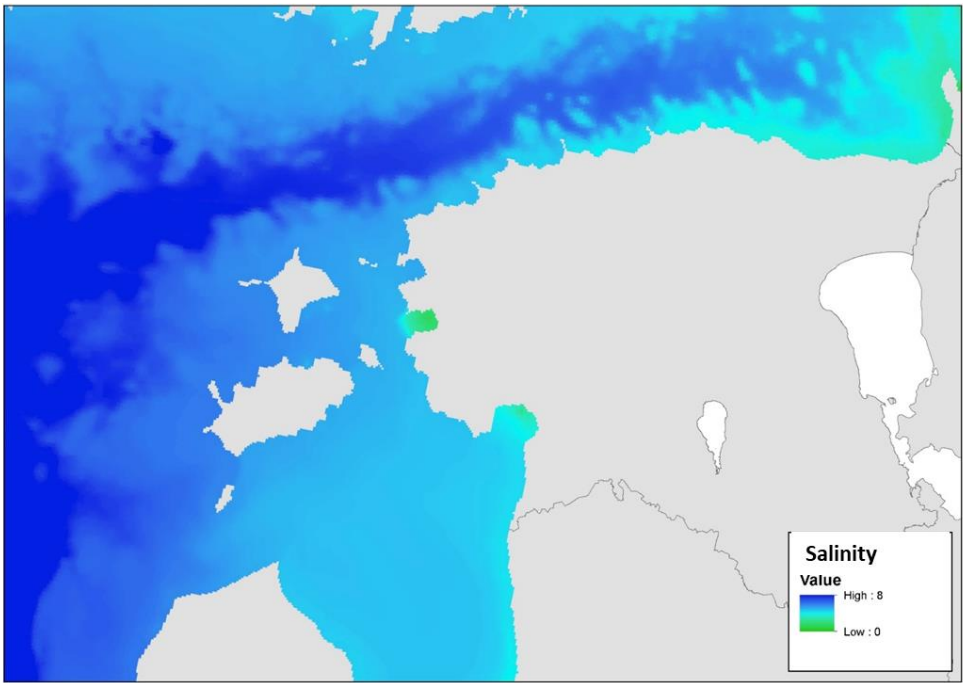

Figure C3. Average salinity of the seawater at Estonian coastal waters. Data from Copernicus portal (BALTICSEA_ANALYSIS_FORECAST_PHY_003_006).

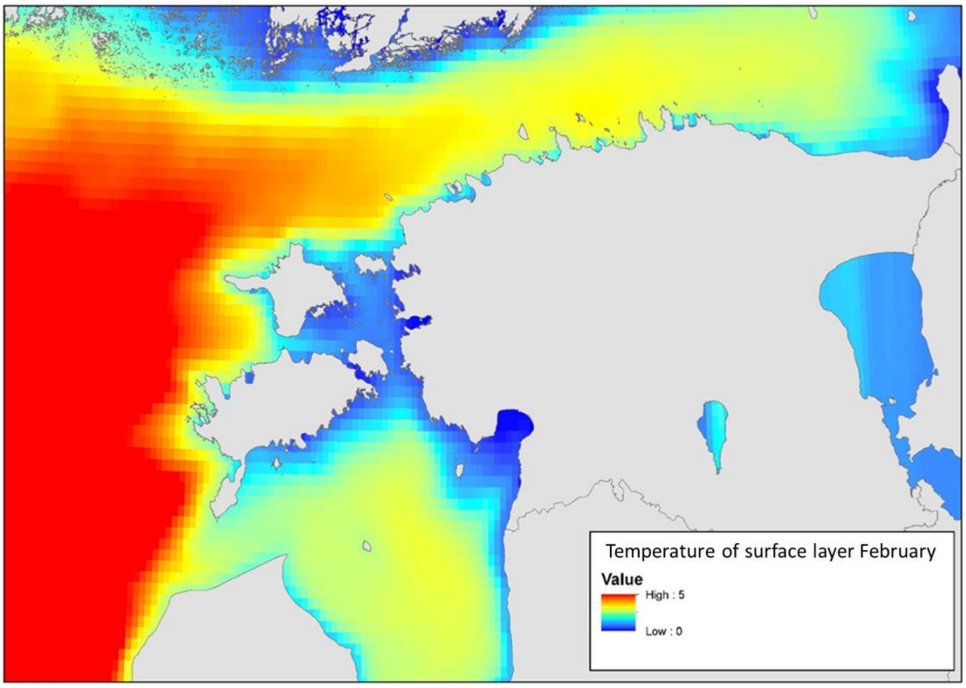

Figure C4. Average water temperature in February, Estonian coastal waters. Data from Copernicus portal (BALTICSEA_ANALYSIS_FORECAST_PHY_003_006).

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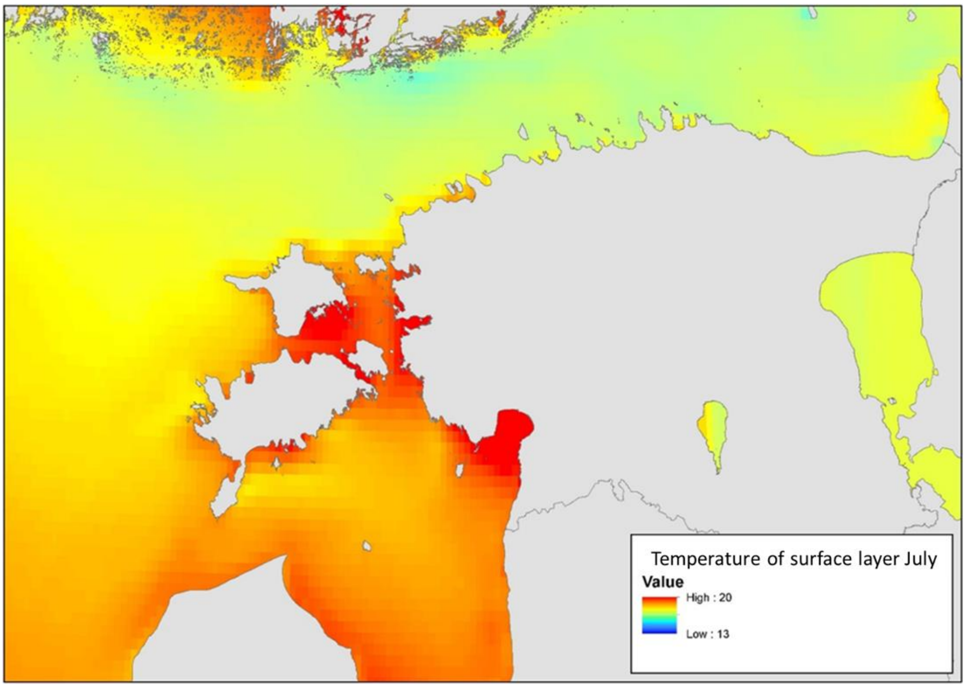

Figure C5. Average water temperature in July, Estonian coastal waters. Data from Copernicus portal (BALTICSEA_ANALYSIS_FORECAST_PHY_003_006).

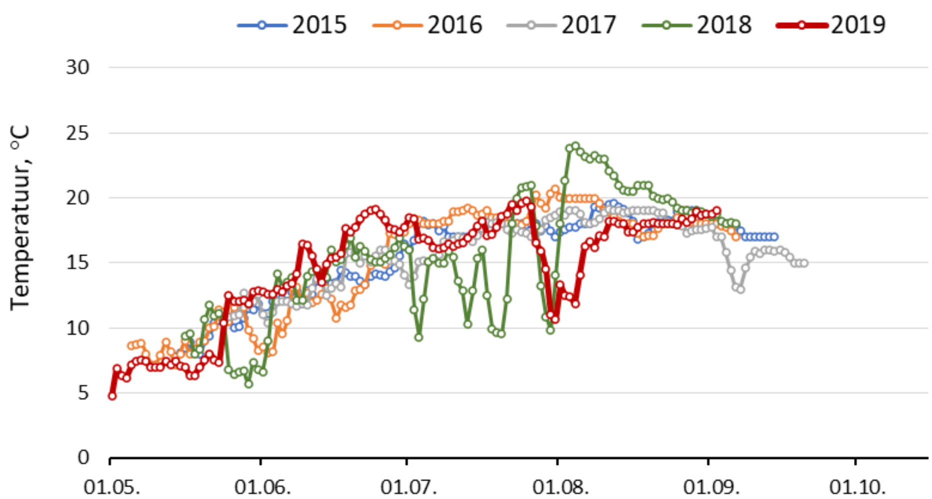

Figure C6. Changes of water temperature at 5 m depth at nearest monitoring station (Küdema Bay) 2015-2019. (Tartu Ülikool & Tallinna Tehnikaülikool 2020).

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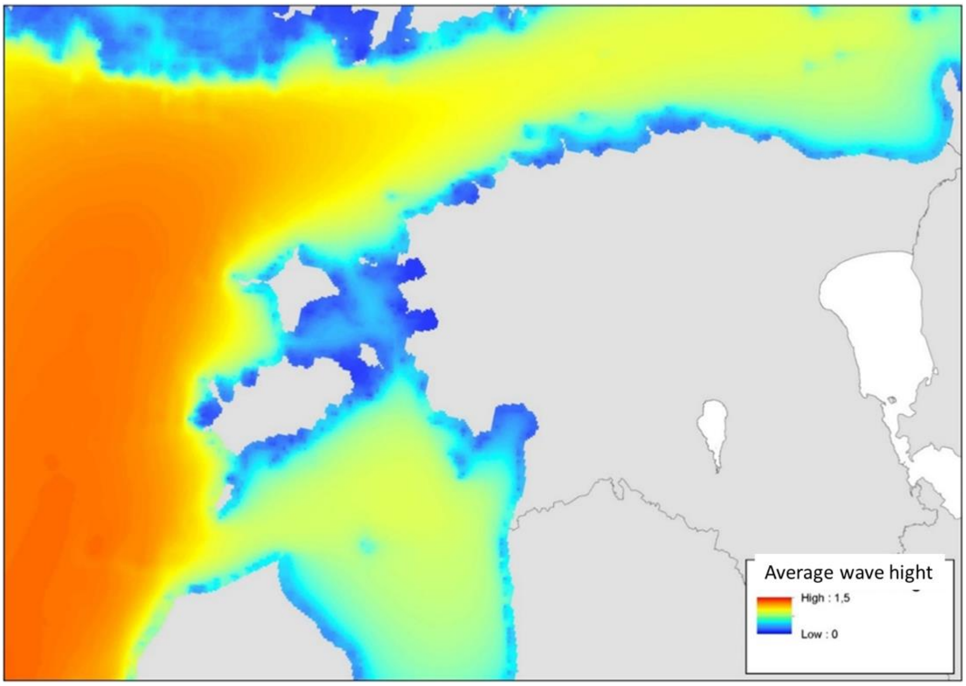

Figure C7. Average wave hight (m). Estonian coastal waters. Data from Copernicus portal (BALTICSEA_ANALYSIS_FORECAST_WAV_003_010).

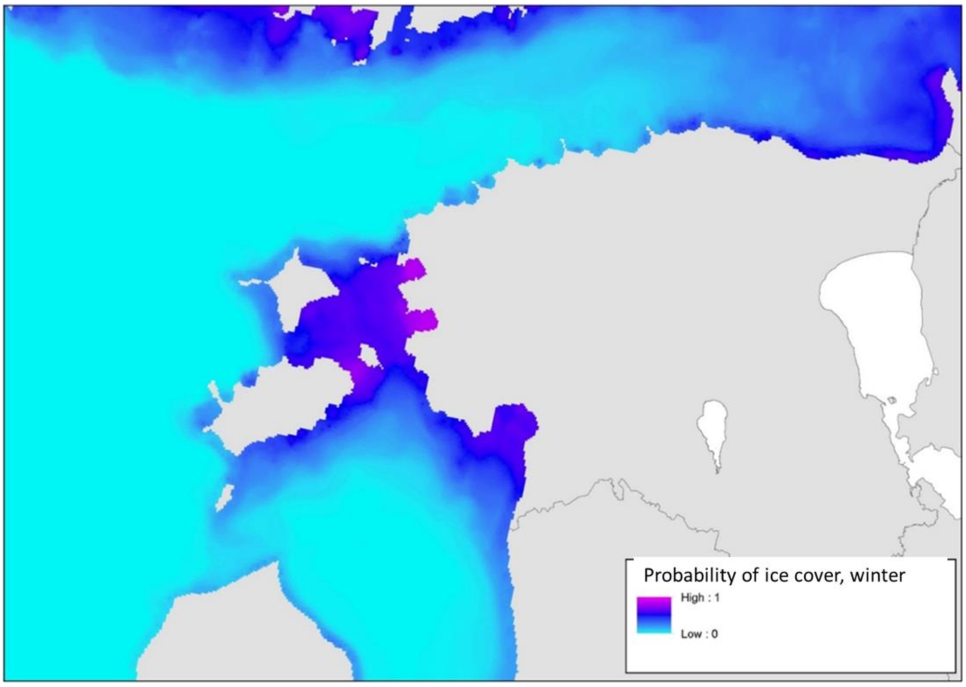

Figure C8. Probability of ice cover during the winter in Estonian coastal waters.

Seabed:

Area of Tagalaht Bay is one of the most suitable for aquaculture along the western coast of West-Estonioan Archipelago because of the bathymetry (relatively deep water bay, open

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towards N). Tagalht Fish farm area is located at the depths 16-22 m. Seafloor at the site is composed of fine sand (Figure C9).

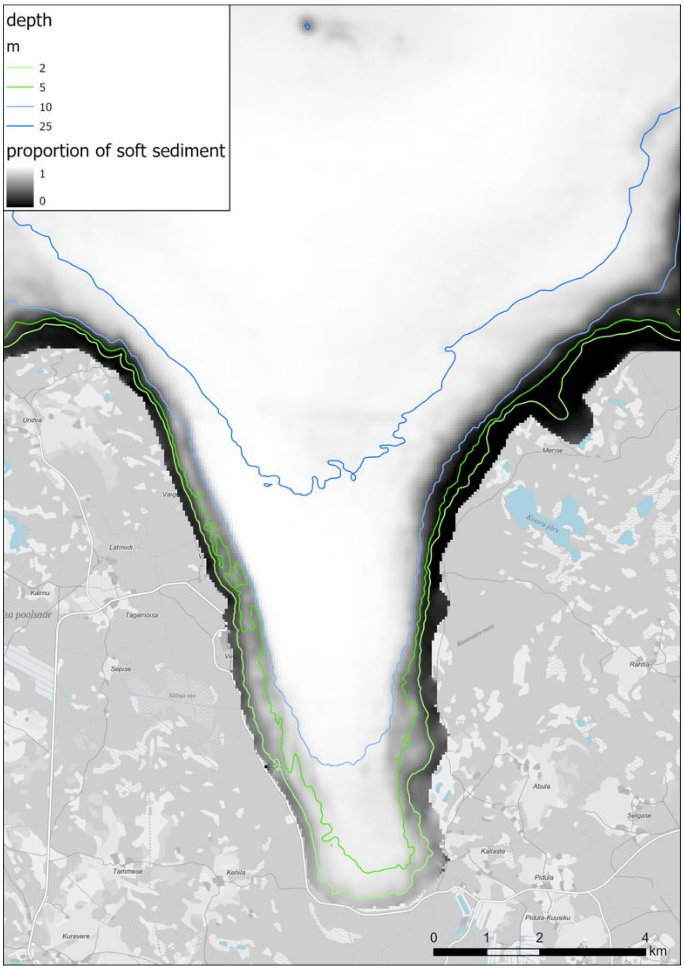

Figure C9. Bathymetry and bottom substrate of the Tagalaht Bay.

Synergies:

Aquaculture is seen as a possible solution to meet the rising demand for fish but only if the sector reduces its use of wild fish in feed as well as its environmental impacts. The cultivation of extractive species along with fish farming (the integrated multi-trophic aquaculture system, IMTA) has a potential to mitigate the adverse environmental effects of fish farming. Recent study (Kotta et al., 2023) explored the potential of mussel (*Mytilus edulis/trossulus*) for bioremediation at finfish farms to develop environmentally sustainable finfish farming solutions in Tagalaht Bay. The study demonstrated that despite suboptimal mussel growth conditions (low salinity), mussel farming has a potential to fully compensate for the discharge of nutrients from fish farms and thereby provide a solution for sustainable fish farming in the region. As such fish farming may become a necessary enabler of economically sustainable mussel farming in the region. Mussel farming facilitates finfish farming licensing whereas finfish farming covers some costs of mussel farming thereby increasing the economic feasibility of this activity in the region.

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Cultivating Ulva provides several synergies with land-based finfish aquaculture. Firstly, Ulva, being an efficient biofilter, can help to mitigate the negative effects of nutrient accumulation in finfish waste water, thereby improving water quality and reducing detrimental nutrient build-up. Secondly, the cultivation of Ulva can provide a source of additional income and improve the sustainability of land-based finfish aquaculture operations. The biomass produced from Ulva cultivation can be used as a feed supplement for finfish, reducing the reliance on imported feed and lowering the overall feed costs. The benefits of integrating LTA into a land-based system are numerous. LTA provides a means to diversify and enhance the productivity of land-based aquaculture operations. By incorporating LTA, the overall productivity of the system can be increased, thereby improving the economic viability of the operation. By incorporating LTA, the system can operate in a more sustainable manner, with reduced reliance on chemical inputs and lower environmental impact. Overall, the integration of LTA into land-based aquaculture systems can provide several synergies and benefits, including improved water quality, reduced reliance on imported feed, increased productivity, and reduced environmental impact.

Licensing:

The Environmental Board has granted Redstorm OÜ an environmental permit (L.VV/329075) for fish farming in Tagalaht. Redstorm OÜ is obliged to conduct an annual marine environment survey. Additionally, the selection of feed used in the farm should prioritize feed that has the least environmental impact and ensures sustainable use of natural resources, while avoiding overfeeding. Records must be kept separately for each type of feed used. The farm is permitted to grow rainbow trout in net pens, each with a diameter of 20 m and depth of 10 m, to be installed in a 17 m deep sea area. The net pen complex covers an area of 9030 m2. The net pens are allowed to be kept in the sea from April until the end of November. Nutrient discharge in the marine net pen farm must not exceed an annual average of 7 grams of total phosphorus and 50 grams of total nitrogen per kilogram of produced fish. Round goby fishing is required from Soela coastal water body and water bodies bordering the Soela coastal water body. It is obligatory to establish a mussel farm in the immediate vicinity of the net pens in Tagalaht as a compensatory measure. If monitoring results reveal that fish farming activities are associated with negative environmental impacts, additional compensatory measures must be implemented to remove nutrients from the marine environment or reduce the load on the marine environment.

Ösel Aquafarms has acquired all needed licenses for operating land-based finfish aquaculture in Küdema Bay area.

Logistics:

Successfully operating a mussel farm in Tagalaht Bay requires a robust logistical framework to address the unique challenges posed by the local marine environment. One of the most significant obstacles in this region is the occurrence of extreme storms, which can inflict substantial damage on the farm's infrastructure, leading to loss of mussels and potentially interrupting the farm's operations. Therefore, the design and construction of the farm must

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incorporate resilience measures to withstand such extreme weather events. This could include the use of flexible, high-strength materials for the farming structures and implementation of storm warning and response protocols. Securely anchoring the mussel farm to the seafloor is another crucial factor to consider. This requires careful site assessment to determine the seabed characteristics and appropriate anchoring methods to ensure the stability of the farming structures in varying water conditions. Nevertheless, one logistical issue that remains to be resolved is the lack of efficient harvesting technology suited to the smaller-sized mussels characteristic of the Baltic Sea. The development or adaptation of harvesting equipment for these specific conditions is necessary to maximize productivity and efficiency. However, the proximity of the farm to the port significantly reduces logistical challenges related to maintenance and monitoring activities. Despite these challenges, the availability of skilled staff, necessary materials, and relevant expertise represents a significant advantage for the successful operation of the mussel farm in Tagalaht Bay.

Incorporating *Ulva* into land-based finfish aquaculture presents several challenges. By utilising the existing facilities provided by our partners at Ösel Harvest OÜ which includes flowing water, indoor temperature control, 24-hour onsite staff, electrical infrastructure and proximity to the Kõiguste field station (Estonian Marine Institute, University of Tartu) many of the logistical challenges associated with this are alleviated. The cultivation process of multiple species in a single system, requires careful management to ensure that each species receives the necessary nutrients and does not negatively impact the others. The availability of onsite flowing water based on groundwater, allows for the tight control of water parameters and reduces biological risks. Additionally, indoor temperature control can facilitate the optimal growth of both finfish and *Ulva*, and the 24-hour onsite staff can monitor the system and respond to any issues quickly. Additionally, being close to the field station helps with the monitoring and analysis of water quality parameters, ensuring that the IMTA system remains healthy and productive. Overall, these existing resources act to meet the challenges of IMTA incorporating *Ulva* into land-based finfish aquaculture, leading to a more sustainable and efficient operation and reducing overall risk.

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Criteria Catalogue

Partner / Site	Hydrodynamics Evaluated	Seabed Evaluated	Synergies Evaluated	Licensing Conditions	Logistics Evaluated
AWI/ Meerwind Süd/Ost OWF	Hydrodynamic analysis has been provided by our partner WindMW and is based on their 2010 report. The tidal current along the German North Sea coast typically flows in a counterclockwise direction from the Netherlands in the southwest to Denmark in the northeast. However, at the case study site, the flow direction varies slightly towards the west and east, dependent upon the tide. The maximum current velocities observed range from 0.56 to 0.64 m/s, averaging at 0.30 to 0.32 m/s.	The seabed in this area consists of sandy bottom, which appropriate for the technology being used. The sandy seabed allows for the installation of various types of anchors such as drill anchors or Danforth anchors.	The case studies synergies primarily relate its ability operate in a congruent fashion with other research projects in the area of the wind farm and taking over surveillance tasks. Additional synergies will include the sharing of vessels, personnel, surveillance and operations and maintenance.	As of June 2023, the AWI has submitted an application to the BSH, the Federal Maritime and Hydrographic Agency in Germany, for the approval of a multi-use open ocean aquaculture within an offshore wind farm. This is the first such application of its kind, which required the BSH to establish the legal framework for examining and potentially approving such a project. Currently, the entire system was applied for as a "closed" measuring point, as this is a common procedure and all components (including the mooring) can be covered in this way.	The site location is situated approximately 120 km from Bremerhaven on the mainland and around 24 km from the offshore island of Helgoland. The management of the farms is conducted from Helgoland as it provides distinct logistical advantages. AWI and WindMW both have facilities on Helgoland, and can utilize their vessels and personnel for the service of the test facility. However, logistical planning can only commence after the installation, mooring, and operation, which is

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					scheduled to begin in early 2024.
AU/ Danish Kriegers Flak	The hydrodynamics in the area of cultivation are characterized by weak currents, averaging up to 1 m/s or 0.5 kn, coming from all directions except from the southeast. The predominant depth-averaged currents flow southwest, while the strongest currents in the area generally originate from the northeast. The cultivation area and lines will be aligned parallel to both the dominant and strongest currents.	The seabed at the site is predominantly sand, with a softly sloping seabed. The depth in the cultivation area ranges from 26 m in the NE corner to 28 m in the SW corner.	The DKF Crew Transfer Vessel (CTV), which operates daily in the area, will visually inspect the over-sea parts of the cultivation structures, lines, and buoys. Observations will be reported on weekly basis to Kerteminde Seafarm and the OLAMUR site leader. The CTV crew will conduct monthly CTD measurements and collect water samples for water chemistry analysis while waiting for service crew in the wind farm. The CTV crew will also exchange elements of monitoring buoys/cameras as needed, and the vessel can potentially provide assistance in the case of technical problems during cultivation operations. The	Seaweed cultivation permits in Danish waters are issued by the Danish Coastal Authorities, while permits for bivalve cultivation are granted by the Danish Fisheries Authorities. However, since the Danish Maritime Spatial Plan does not currently designate DKF as a 'shellfish aquaculture zone,' prior permission from the Danish Maritime Authorities is required for bivalve cultivation before submitting an application to the Fisheries Authorities. As of now (June 2023), the seaweed cultivation license for DKF is anticipated to be approved in June/July 2023, while the bivalve license application is pending approval from the Danish Maritime Authorities.	Marker buoys and drill anchors will be deployed, with a large vessel chartered through FOGA for this purpose. The Swedish company Carapax, specializing in drill anchor establishment, will also be chartered. Kerteminde Seaweed will be responsible for establishing and decommissioning the seaweed/mussel cultivation system using their own large vessel, while Kerteminde Seafarm will handle the deployment of seaweed lines, mussel spat collectors, and maintenance operations using their designated smaller vessel. Visual inspections of the farm

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			CTV may support the decommissioning of the cultivation system.		will be conducted daily by the Vattenfall CTV crew. The limited number of suitable working days at sea in the challenging environment of DKF will be partially mitigated by the CTV crew's regular inspections, freeing Kerteminde Seafarm from constant presence. Additionally, using the Kerteminde Seafarm vessel for monitoring and maintenance operations will prevent conflicts of interest, allowing the CTV to be fully utilized by Vattenfall/Siemens on days with favorable working conditions at sea.
UT/ Tagalaht Bay	Tagalaht Bay's low salinity restricts the size of mussels, although the high phytoplankton biomass facilitates their initial growth. The mussel farm in	The Tagalaht Bay area in the western coast of the West-Estonian Archipelago is characterized by relatively deep water and an open orientation towards the	Mussel farming can effectively compensate for nutrient discharge from finfish farms, offering a sustainable solution. Cultivating *Ulva* in land-	Redstorm OÜ has obtained an environmental permit from the Environmental Board to conduct fish farming in Tagalaht Bay. The permit requires annual	Extreme storms are a significant concern, necessitating the design of resilient structures and implementation of storm warning protocols.

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	the bay utilizes larval recruitment and employs a smart farming system with nets placed at specific depths and cleaned/harvested by specialized machines. In terms of finfish farming, the bay's water movement patterns ensure adequate oxygenation and nutrient cycling, while its semi-enclosed nature provides protection against extreme weather conditions. The favorable water temperature and salinity levels in the bay contribute to optimal finfish growth.	north. The Tagalaht Fish farm is situated at depths ranging from 16 to 22 meters, with the seafloor predominantly consisting of fine sand and is suitable for aquaculture activities.	based finfish aquaculture systems improves water quality, reduces feed costs, and enhances overall productivity while minimizing environmental impact.	marine environment surveys, prioritization of environmentally friendly feed selection, and separate record-keeping for each feed type used. The farm is authorized to grow rainbow trout in net pens, with specific dimensions and a designated sea area. Nutrient discharge limits have been set, and the establishment of a nearby mussel farm is mandated as a compensatory measure. Ösel Aquafarms has acquired all necessary licenses for land-based finfish aquaculture in Küdema Bay.	Secure anchoring to the seafloor is crucial, requiring careful site assessment and appropriate anchoring methods. The lack of efficient harvesting technology for smaller-sized mussels is an unresolved issue. However, proximity to a port reduces logistical challenges, and the availability of skilled staff and necessary resources is advantageous. Incorporating Ulva into land-based finfish aquaculture presents challenges, but existing facilities, such as flowing water, temperature control, and onsite staff, alleviate many logistical concerns.

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References

Buck BH, Grote B (2018) Seaweed in High Energy Environments: Protocol to move *Saccharina* Cultivation Offshore. In: Charrier B, Wichard T, Reddy CRK (Eds.): Protocols for Macroalgae Research. CRC Press, Taylor & Francis Group. ISBN-13: 978-1498796422 - ISBN-10: 1498796427. https://doi.org/10.1201/b21460

FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome.

Heasman KG, Scott N, Smeaton M, Goseberg N, Hildebrandt A, Vitasovich P, Elliot A, Mandeno M, Buck BH (2021) New system design for the cultivation of extractive species at exposed sites -Part 1: System design, deployment and first response to high-energy environments. Applied Ocean Research 110: 102603 - https://doi.org/10.1016/j.apor.2021.102603

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F.R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Jonsson, P.R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M.M., Mühl, M., Sandman, A.N., Orav-Kotta, H., Orlova, M., Skov, H., Rissanen, J., Šiaulys, A., Vidakovic, A. and Virtanen, E. 2020. Cleaning up seas using blue growth initiatives: mussel farming for eutrophication control in the Baltic Sea. STOTEN, 709, 136144.

Kotta, J.; Orav-Kotta, H.; Jänes, H.; Hummel, H.; Arvanitidis, C.; van Avesaath, P.; Bachelet, G.; Benedetti-Cecchi, L.; Bojanic, N.; Como, S.; Coppa, S.; Coughlan, J.; Crowe, T.; Dal Bello, M.; Degraer, S.; Juanes de la Pena, J. A.; Fernandes de Matos, V. K.; Espinosa, F.; Faulwetter, S.; Frost, M.; Guinda, X.; Jankowska, E.; Jourde, J.; Kerckhof, F.; Lavesque, N.; Leclerc, J-C.; Magni, P.; Pavloudi, C.; Pedrotti, M. L.; Peleg, O.; Pérez-Ruzafa, A.; Puente, A.; Ribeiro, P.; Rilov, G.; Rousou, M.; Ruginis, T.; Silva, T.; Simon, N.; Sousa-Pinto, I.; Troncoso, J.; Warzocha, J.; Weslawski, J. M. 2017. Essence of the patterns of cover and richness of intertidal hard bottom communities: a pan-European study. Journal of the Marine Biological Association of the United Kingdom, 97, 525-538.

Kotta, J.; Stechele, B.; Barboza, F.R.; Kaasik, A.; Lavaud, R. 2023. Towards environmentally friendly finfish farming: A potential for mussel farms to compensate fish farm effluents. Journal of Applied Ecology, https://doi.org/10.1111/1365-2664.14422.

Landmann J, Fröhling L, Gieschen R, Buck BH, Heasman K, Scott N, Smeaton M, Goseberg N, Hildebrandt A (2021) A new system design for the cultivation of extractive species at exposed sites - Part 2: Experimental modelling in waves and currents. Applied Ocean Research 113: 102749 - https://doi.org/10.1016/j.apor.2021.102749

Schupp MF, Bocci M, Depellegrin D, Kafas A, Kyriazi Z, Lukic I, Schultz-Zehden A, Krause G, Onyango V, Buck BH (2019). Towards a Common Understanding of Ocean Multi-Use. Frontiers in Marine Science 6(165): 12 p. https://doi.org/10.3389/fmars.2019.00165

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Wind MW (2010) Offshore-Windpark Meerwind Ost und Süd: Design Basis für Gründungsstrukturen. Berichts-Nr. 90118-DB-01. 24-55.

"Funded by the European Union, grant agreement NO 101094065. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them."