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# Deliverable 10.1 - State of the Art revisions for LTA in OWFs

Work Package 10

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| **Abstract** | With the continued intensity under which developments are occurring in the offshore low trophic aquaculture and nature restoration fields, a revision on state-of-the-art developments since the project inception has been conducted in order to benchmark the proposed project designs against further developments over the past year. The results of this study have been outlined in this deliverable. |
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| | |
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| AIS | Automatic Identification System |
| LTA | Low-Trophic Aquaculture |
| OWF | Offshore Wind Farm |
| TRL | Technology Readiness Level |
| WP | Work Package |
| IMTA | Integrated Multi-Trophic Aquaculture |
| SoA | State of art |
| NID | Nature-Inclusive Nature |
| SMF | Submersible Mussel Farm |
| SST | Sea Surface Temperature |
| USV | Unmanned Surface Vehicles |

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# Executive Summary

The offshore aquaculture industry, with a focus on oysters, seaweeds, and mussels, has continually developed since the inception of the ULTFARMS project, 12 months prior to the submission of this deliverable. Therefore, the project has undertaken a critical review on the state-of-the-art for low-trophic aquaculture activities, focusing on mussel, oyster, and seaweed, leading to the identification of advancements since the initial conception and writing of the proposal. This includes the development of new techniques and methodologies that enhance efficiency and sustainability, risks and challenges associated with the implementation of Long-Term Agreements (LTA) within Offshore Wind Farms (OWF) in offshore settings, environmental concerns, regulatory compliance, technological limitations, and financial constraints. In response, the revision has explored potential solutions and strategies such as the adoption of new technologies, collaboration with regulatory bodies, investment in research and development, and the establishment of best practices and standards. The updated state-of-the-art provides context for the solutions to be further developed within the project, emphasizing continuous innovation, collaboration among stakeholders, adherence to environmental and ethical principles, and serving as a valuable resource for guiding informed decisions in the offshore aquaculture industry.

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# 1. Introduction

## 1.1 Background

The primary mission of the ULTFARMS project is to "demonstrate profitable, sustainable, and eco-friendly low trophic food (molluscs & seaweed) production from offshore aquaculture activities within wind farms in the Nort Sea and Baltic Seas." (ULTFARMS website). As part of this mission the project aims to move beyond the current Low-Trophic Aquaculture (LTA) systems with novel engineering, technical, ecological and biological processes to optimise the production of such systems in harsh offshore conditions and/or low-salinities and support their integration with Offshore Wind Farms (OWFs). To go beyond the current state of the art, ULTFARMS will build upon previous efforts to adapt and refine various technical solutions enhance the productivity, safety, and ecological friendliness of LTA within OWFs. The scope of the project is not limited to the implementation of LTA in OWFs, it also includes an assessment of the ecologically positive dimension and the maximization of the joint potential of different activities.

ULTFARMS builds on knowledge that was gained in previous projects on offshore multi-use and LTA, including MERMAID, Wier and Wind, IMPAQT, HiSea, Coastbusters, BONUS-OPTIMUS, EDULIS and the ongoing UNITED and MUSICA projects. This knowledge exchange comes from a blending of partners whom have worked on these various projects as well as communication with development partners in these projects. These projects have increased the Technological Readiness Level (TRL) of the technology and design for LTA in OWFs. Although each has incrementally improved solutions towards commercially exploitable levels, i.e. "Actual system proven in operational environment" (European Commission, 2022), this target level has not yet been achieved. To further advance to such a stage of development, ULTFARMS will deploy six demonstration pilots that will carry out LTA activities within OWFs in the North Sea and Baltic Sea. An overview of the pilots, with information on the location, the cultivated species, and the technological readiness level, is presented in Table 1.1.

*Table 1.1: Overview of ULTFARMS demonstration pilots (see Annex I for definitions).*

| Pilot | Region | LTA species | TRL | |
|---|---|---|---|---|
| | | | Present | Aim |
| Samsø | Danish Baltic Sea | Mussel | 5 | 8 |
| Anholt | Danish Baltic Sea | Seaweed & Mussel | 5 | 7 |
| FINO2 | German Baltic Sea | Seaweed | 5 | 7 |
| FINO3 | German North Sea | Seaweed, Mussel & oyster | 6 | 7 |
| Borssele | Dutch North Sea | Mussel | 6 | 9 |

| | | | | |
|---|---|---|---|---|
| Belwind | Belgian North Sea | Seaweed, Mussel & oyster | 6 | 8 |

## 1.2 Scope of this deliverable and link to other tasks

This deliverable reports on the results of the first task of the work package (WP) "Roadmap to Innovation and Upscaling" (WP10). Task 10.1 involves performing a revision of the current state of the art for low-trophic aquaculture in offshore windfarms, specifically within the context of seaweed, mussels, and oysters, in order to provide an up-to-date summary of the risks, challenges and solutions to implementation. This overview is the result of a follow-up desk study from that which had taken place at the project inception and relies on the expertise and know-how of project partners as well. In a way, this first task of WP10, the review of the state of the art at the beginning of the project, can be considered as a starting point. Details about the system design that will be tested in each of the pilots will be reported in deliverables that are produced within WP3 "System Design: Mariculture Structures, Renewables, and Sensors". Over the course of the project, knowledge will be gained from the implementation off the innovative LTA solutions at six offshore pilot sites. Within the final task of WP10, the gained knowledge will be used to create an integrated roadmap for upscaling, addressing viable, sustainable, and innovative aquaculture, which can be used to facilitate the adoption of the innovative solutions in future applications of LTA in OWFs.

# 2. Oyster aquaculture in OWFs

Low Trophic Aquaculture (LTA) designs and technologies, for example those for oyster cultivation and restoration, have been gaining increasing attention as demands for marine proteins and biomass have increased over the past two decades, and is projected to continually increase. These innovative approaches aim to minimize environmental impacts and improve sustainability. Examples of such designs and technologies are:

- Floating Oyster Farms: Floating oyster farms are being increasingly deployed in Australia. These farms utilize floating platforms that support the growth of oysters in suspended culture systems. The platforms are designed to withstand ocean conditions and allow for efficient cultivation and harvesting. The TRL of this technology is relatively high, ranging from TRL 7 to TRL 9, indicating its successful deployment and commercialization (DPI Fisheries and Aquaculture Management, Management & Administration Unit, 2021)
- Submerged Oyster Farms: Submerged oyster farming involves cultivating oysters below the water's surface, typically using racks or cages. This method helps protect the oysters from adverse weather conditions and reduces interactions with other marine organisms. Submerged oyster farms have been implemented in nearshore areas, For Offshore use their TRL is

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still in the medium range (TRL 4 to TRL 6), as further research and development are needed to optimize the design and scale up production.

- Remote Monitoring Systems: Remote monitoring systems play a crucial role in designs for offshore oyster aquaculture. These systems utilize sensors, cameras, and data analytics to monitor water quality parameters, environmental conditions, and oyster growth. They enable real-time monitoring, early detection of issues, and informed decision-making. The TRL of remote monitoring systems is relatively high, ranging from TRL 7 to TRL 9, as they are extensively used in different offshore operations. The critical variables for monitoring within oyster farms are often also monitored in other operations, such as fish farming, offshore wind and energy production platforms, and biodiversity and monitoring. Therefore many sensors are available for such applications, however, the unique difficulty if the attachment of such sensors to the aquaculture system, if this is the attachment point chosen for, and the introduction of additional shear stresses on the attachment point and potential additional stresses and damages placed on the monitoring equipment.
- Biofouling Mitigation: Biofouling, the accumulation of organisms on submerged structures, can negatively impact oyster growth and farm operations. LTA designs incorporate various biofouling mitigation strategies, such as antifouling coatings, ultrasonic devices, and biocides, to minimize fouling. The TRL of biofouling mitigation technologies varies, with some solutions at higher TRLs (6 to 9) and others still under development (TRL 4 to TRL 6). However, to allow for human consumption, biotoxic antifouling is not permittable.
- Integrated Multi-Trophic Aquaculture (IMTA): IMTA systems combine multiple species, such as mussels, finfish, and seaweed, to optimize resource utilization and ecosystem services. Offshore oyster aquaculture can be integrated with other marine organisms to create sustainable and resilient ecosystems. IMTA is an area of active research and development, with a TRL ranging from 4 to 7, depending on the specific implementation and the level of integration achieved.

Overall, designs and technologies in offshore oyster aquaculture are at different stages of development and deployment. While some technologies, such as floating oyster farms and remote monitoring systems, have reached higher TRLs and are commercially available, others, like submerged oyster farms and certain biofouling mitigation strategies, require further research and optimization to achieve widespread implementation and commercial viability.

## 2.1 Original State of Art (Design SoA)

Mollusc cultivation, an emerging field in aquaculture, has gained significant momentum as researchers and industry professionals explore its potential for sustainable seafood production. The cultivation of molluscs, including oysters and blue mussels, has demonstrated promising ecological and economic benefits. In this regard, the ongoing activities at the FINO 3 test site offer valuable insights and opportunities for the commercialization of mollusc cultivation practices. Furthermore, the Belgian BELWIND pilot has successfully harvested oyster crops and had a positive outcome in their UNITED project oyster restoration activities. This, along with novel monitoring and modelling efforts as reflected in Stechele 2022 and 2023 will be carried over into the ULTFARMS project to further elaborate on the suitability of such species in the North and Baltic Seas.

Within the Belgian pilot, the activities undertaken in the UNITED project will be refined and taken further. This includes adaptions to the nature inclusive scour protection designs and oyster bed restoration hard bottom substrates to improve the settlement chances of the oyster spat, increase the reef restoration activities, and enhance the yield from the oyster growth medium and structures. These activities, taking place alongside one another, have the opportunity to serve as a template for self-sustaining oyster aquaculture, having a grow apparatus in close proximity to restored oyster beds take advantage of the restored reef's natural spawning cycle to natural seed the growing medium and yield commercial oyster stocks for consumption. This would eliminate the need for importing oyster spat, which is currently difficult as the spat need to be certified Bonamia free, a disease which is plaguing European shellfish stocks. As this pilot is taking place within an active wind park site, with the operator as a consortium partner, it has a strong potential to test new adapted structures and prove the validity of a naturally seeding method for growing commercial stocks of oysters in the North Sea. With the strong ties to regulatory bodies and the pre-existing network of stakeholders engaged with through UNITED, the developments in this pilot are poised to have rapid adoption within Belgium and beyond.

The FINO 3 test site has become an ideal platform for testing and refining various aquaculture projects. With its established connections to relevant regulatory agencies and extensive knowledge of the German market, the FINO 3 test site holds the potential to make significant contributions towards the commercial uptake of mollusc cultivation. To facilitate the successful commercial implementation of mollusc cultivation, a comprehensive business plan has been meticulously developed. This plan encompasses the utilization of a commercial multi-use strategy, integrating Low-Trophic-Aquaculture (LTA) and offshore wind energy production. The feasibility study conducted as part of the ongoing UNITED project has laid the foundation for this business plan, which is continuously updated and refined.

The techniques and methodologies previously explored in the Belgian pilot site within the UNITED consortium, specifically focused on oyster cultivation, are now being considered for transfer and testing at the FINO 3 test site. Leveraging the lessons learned from the Belgian pilot, the FINO 3 test site will serve as a valuable arena to assess and enhance the effectiveness and sustainability of mollusc cultivation within the ULTFARMS activities.

By integrating these proven techniques into the FINO 3 test site activities, the scientific knowledge base surrounding mollusc cultivation will be further consolidated. This integration will facilitate practical implementation and scalability of mollusc cultivation in offshore environments, promoting the diversification and expansion of aquaculture practices. Moreover, this endeavor aligns with the principles of environmental stewardship, fostering sustainable production of nutritious seafood.

## 2.2 Advances In SoA

Recent advances in offshore oyster aquaculture show progress in various aspects, including site selection methods, innovative technologies for oyster detection and counting, design and analysis of sub-surface longline marine farms, hydrodynamics research, and the integration of remote sensing and bioenergetics modelling for optimal site selection and improved production. In a review paper by Ubina & Cheng (2022), various unmanned system technologies were explored in the context of aquaculture farm monitoring and management, various ROV and automated submersible systems which autonomously navigate the aquaculture region, taking biogeochemical measurements as well as direct measurements of the oysters themselves to check on the growing conditions as well as the actual growth and health of the oyster crops. Sadrfaridpour et al. (2021) presented interesting developments in oyster detection and counting using the BlueRobotics BlueROV2 equipped with a GoPro camera and LED lights. Their study showcased promising results in the field of oyster monitoring. Palmer et al. (2020) conducted a study focusing on remote sensing-driven growth modelling of Pacific oysters (*Crassostrea gigas*) to support offshore aquaculture site selection. Their approach integrated satellite remote sensing data and Dynamic Energy Budget modelling to identify optimal locations for aquaculture and generate industry-relevant indicators, such as time to market weight and quality index. A similar approach is being utilized by the Belgian pilot partners fin their oyster pilot, following up on the growth and energy budget modelling work undertaken within the UNITED project. The Palmer et. al. study aimed to improve oyster production through offshore cultivation in France, and lessons learnt can be adapted to the Belgian partner case; similar approach, combining oyster bioenergetics modelling and input from satellite data, was applied in South Africa and will also be referenced in the monitoring and modelling activities (Krupandan et al., 2022). Palmer et al., (2021) also expanded on this approach to include climate change scenarios and assess future uncertainty for offshore aquaculture. Several priority areas for the development of offshore Pacific oyster cultivation were highlighted within Europe and northwestern Africa, further modelling work to be done in ULTFARMS will make use of these climate change projection scenarios and build on such work to

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look at suitability indices across the North and Baltic seas. Other advancements based on Dynamic Energy Budget modelling for different species of oysters are presented in Stechele et al. (2022; 2023) from the UNITED pilot cases, upon which the Belgian case is based on. This demonstrates that the oyster modelling and research direction is indeed in line with other activities and on the cusp of the state of the art. These models provide a georeferenced dataset that can be used as a basis for habitat suitability maps, site selection, optimal farm configuration and carrying capacity of production areas.

In the context of structural and engineering design, the design and analysis of a sub-surface longline marine aquaculture farm, intended for co-existence with an offshore wind farm, was recently conducted in Korea (Boo et al., 2023). The pilot farm, covering an area of 200 m x 200 m, used multiple polypropylene ropes and buoys supported by catenary mooring arrangements. The study demonstrated the farm lines' sufficient fatigue capacity and adherence to industry design requirements to be viable at larger scales. Such an arrangement is being implemented at two of the pilot sites within the ULTFARMS project, and studies such as Boo et al. will serve as bolstering evidence as to the viability of the design in various hydrodynamic and oceanic conditions. Landmann (2023) explored the hydrodynamics of bivalve offshore aquaculture in their PhD thesis. The thesis involved physical experiments and on-site testing of a newly designed aquaculture system for oysters and mussels and was published as a two-piece contribution consisting of two interconnected papers. The first paper, Landmann et al. (2021), details physical laboratory tests of a new submersible cultivation system for bivalve farming called "Shellfish Tower", consisting of a rectangular cage with a central buoyancy element and sub-units for crop cultivation. In the second paper, Heasman et al. (2021), the technical feasibility of this system was tested in exposed waters in New Zealand. The structure exhibited a design tolerance of significant wave height of over 7 m and currents of over 0.8 m/s. Similar conditions exist in some of the ULTFARMS sites where oyster cultivation will be explored and expanded upon, and these design specifications taken into consideration in the execution of ULTFARMS.

## 2.3 Overview

### Risks

Offshore oyster cultivation can be an increasingly popular method for meeting the growing demand for oysters while also protecting and restoring natural oyster populations. However, like any form of aquaculture, there are certain known risks associated with offshore oyster farming. It is important to be aware of these risks in order to develop sustainable and resilient practices.

One significant risk is the potential for disease outbreaks within oyster populations. Oysters can be susceptible to various pathogens, including bacteria and viruses, which can spread rapidly in dense farming environments. These diseases can cause significant mortality and impact the overall health of the oyster population. To mitigate this risk, farmers often implement strict biosecurity measures such as regular monitoring, quarantine protocols, and appropriate water quality management.

Another risk is the impact of extreme weather events. Offshore oyster farms are exposed to the forces of nature, including storms, hurricanes, and tidal surges. These events can result in physical damage to infrastructure, disruption of farm operations, and even complete loss of oyster stocks. Implementing robust engineering designs, securing farming structures, and developing emergency response plans are essential to minimize these risks.

The presence of oyster aquaculture anchoring system can alter the seabed habitat, potentially affecting other species in positive or even negative ways. Best management practices, such as proper site selection, can help mitigate these impacts, along with clear intentions in regard to nature inclusive design and determination of what the ecological baseline and regional or supranational objectives for such regions are. In the context of using oyster restoration or aquaculture as enablers of ecosystem design and development, strict adherence to do no harm principals and consultations with environmental regulatory agencies is required so that alterations in the natural ecosystem are not used as greenwashing.

Finally, market risks should not be overlooked. As with any agricultural product, oyster farmers are subject to market fluctuations and consumer demand. Variations in price, competition, and changes in consumer preferences can affect the profitability and viability of offshore oyster farms. Diversifying markets, establishing strong relationships with buyers, and promoting the sustainability and quality of the product can help mitigate these risks.

In conclusion, offshore oyster cultivation presents several known risks that need to be carefully managed. Disease outbreaks, extreme weather events, environmental impacts, and market risks all require proactive measures and ongoing research to ensure the long-term sustainability of this form of aquaculture. By addressing these risks, stakeholders can work towards a more resilient and sustainable offshore oyster farming industry.

## Challenges

Offshore oyster cultivation faces several known challenges. These include harsh offshore conditions where the environment can be particularly unforgiving, and storms have the potentiality of decimating crops over the 18-24 months it often takes to achieve successful yield. With expected growing frequency and intensity of such North and Baltic Sea storms, this challenge and limitation is set to increase in potentially severity in the years to come. Another challenge is the hostile physical conditions at the Belwind pilot site. The site's conditions are not conducive to easy oyster cultivation and require special considerations and adaptations. Additionally, the long sea routes at, particularly to the FINO3 site, pose logistical challenges for oyster cultivation operations, specifically in regular maintenance and observation type trips. This is further exacerbated by the continued and expanding energy crisis, with the increasing cost of fuels making such trips a significant factor in the commercial viability of such activities.

Furthermore, the anchoring of offshore infrastructure presents a significant challenge. Ensuring stable and secure anchorage for the necessary equipment and structures is crucial for successful oyster cultivation. Developing efficient, secured, and environmentally friendly systems for anchoring is critical to the industry, and ensuring the reliability thereof is a pre-requisite for integrating LTA in OWF activities, as lost lines can cause significant and costly damage. In the face of logistical issues of site visits, lost or damaged lines due to anchoring failures cannot always be speedily remedied. Lastly, fouling, the accumulation of unwanted organisms on the infrastructure, poses an ongoing challenge. Managing and preventing fouling is essential for maintaining the health and productivity of oyster cultivation systems.

In summary, offshore Oyster cultivation encounters challenges related to harsh conditions, long sea routes, hostile environments, anchorage, and fouling. Overcoming these challenges is vital for the successful implementation and sustainable growth of offshore oyster cultivation initiatives.

- **Potential solutions**

The ULTFARMS project is implementing a range of solutions and techniques to tackle challenges and risks associated with LTA in OWFs. These initiatives are aimed at supporting the implementation of LTA and ensuring its success within OWFs. One of the key areas of focus is the development of oyster cultivation techniques at the FINO3 pilot site. Lessons learned from the Belgian site in the UNITED project are being explored and tested to establish effective methods for oyster production.

To enhance monitoring and reduce costs, the project is also working on the development of new cost-effective monitoring techniques. These innovative approaches will enable the assessment of LTA system performance and environmental impact in a more efficient and affordable manner. This includes proxy sensors, cost effective surrogate sensors which can monitor variables with clearly defined relationships to target monitoring variables. In this way, a proxy variable is monitored via cost-efficient sensors and a mathematical relationship between the measured variable and target variable developed to allow for a type of synthetic sensor to be used in place of more costly and fragile sensors.

Integration of the HiSea service is another important aspect of the project. This service provides predictions and forecasts, based on real-time data on water quality and environmental conditions, which will be utilized to enhance monitoring and decision-making processes within ULTFARMS. This combined with developed higher resolution models for specific pilot sites will allow for a comparison of coarse resolution open access data to be contrasted against built-for-use high resolution systems to determine the degree of benefit of such applications. Additionally, the project aims to leverage the renewable energy generated on-site in OWFs to power the LTA systems. This approach will reduce dependence on external energy sources and enhance the sustainability of LTA operations as well as support the monitoring capacities offshore. Sensor technology plays a crucial role in the project, with the application of classical load cells, accelerometers, depth sensors, scanning sonars, tilted transducers, and multibeam sonars. The collected sensor data is integrated with existing environmental measurements to improve farm models and enable better monitoring and interpretation.

The ULTFARMS project adopts a circular economy approach by utilizing waste shell material from mollusc production. This waste shall be repurposed as smart materials and possible feed for livestock, contributing to a more sustainable and resource-efficient system.

Nature-inclusive design (NID) principles are being incorporated into the project to enhance biodiversity, ecosystem services, and habitat quality within OWFs. These design considerations will help create a more ecologically friendly environment. In terms of infrastructure, the project is exploring the use of submerged longline systems for oyster aquaculture. This system offers a highly efficient and sustainable method for oyster production. The ULTFARMS project shall also investigates the "artificial reef effect" through a proposed standardized monitoring protocol that shall be developed and agreed upon. This allows for a deeper understanding of the ecological benefits that LTA systems can provide. Biodiversity assessment is conducted through a combination of morphological identification and metabarcoding techniques to evaluate the biodiversity of hard-substrate habitats. To minimize environmental impact, nature-inclusive scouring protection materials are being explored, ensuring protection against erosion while promoting biodiversity.

The project incorporates advanced monitoring techniques such as using eDNA techniques to monitor shell-fish diseases and employing video monitoring systems and acoustic sounders to gather information on local species biodiversity. Bottom cultivation systems for oysters are being developed to optimize productivity and sustainability, while improvements are also made to aquaculture grow-out infrastructure, including nets, droppers, baskets, and lanterns. To prevent the accumulation of unwanted organisms, antifouling measures such as antifouling rings or brushes are employed on LTA infrastructure. Data collected by sensors is remotely transmitted, enabling real-time analysis and decision-making. Additionally, webcams and GPS trackers are utilized to monitor the LTA system for breakages or malfunctions, ensuring timely maintenance and repairs. For enhanced tracking and monitoring, AIS buoys are proposed to be employed, improving operational safety and security within the ULTFARMS project. These comprehensive solutions and techniques are implemented within the ULTFARMS project to address challenges, mitigate risks, and support the successful implementation of LTA in OWF.

# 3. Seaweed aquaculture in OWFs

Seaweed aquaculture in OWF has gained significant attention as a promising solution for sustainable food production, environmental conservation, and maximizing resource utilization. Several applications and TRL have emerged in this field, showcasing the potential for integrating seaweed cultivation within OWF designs. One such application involves using seaweed cultivation as a form of ecological enhancement within OWFs. Seaweeds can provide valuable ecosystem services, such as habitat creation, nutrient uptake, and carbon sequestration, thereby promoting biodiversity and improving the overall environmental performance of the wind farm. This application has reached a relatively high TRL, with successful pilot projects and demonstration sites established in various warmer regions worldwide. However, mainly in nearshore environments. Additionally, the commercial cultivation of seaweed for biomass production and various product developments. Seaweeds have a high growth rate, do not require freshwater or arable land, and can be harvested multiple times a year. This makes them a promising feedstock for biofuels, animal feed, fertilizers, and even food products. While the commercial-scale implementation of seaweed aquaculture in OWFs is still at a relatively lower TRL, there are ongoing research and development efforts to optimize cultivation techniques, address logistical challenges, and assess market viability,

To enhance the integration of seaweed cultivation within OWF designs, several technology advancements shall be explored. These include the development of specialized cultivation systems that can withstand harsh offshore conditions, such as floating or submersible structures, automated monitoring and control systems, and innovative harvesting methods. While these technologies are still in the early stages of development, they show promising potential to support the scaling-up of seaweed aquaculture in OWFs.

## 3.1 Original State of Art (Design SoA)

In the context of seaweed cultivation at the proposal submission stage, several noteworthy considerations emerge. Firstly, it is imperative to recognize the pivotal role of European seaweed production within circular food systems. This recognition underscores the importance of optimizing production while taking into account the carrying capacity of European seas and its applications in the European food system, as highlighted by van de Burg et al. (2021). Central to this endeavor is the aspiration to achieve maximum seaweed production while minimizing adverse environmental impacts. This is a complex challenge, particularly in areas characterized by turbulent waters with high turbidity, such as the North and Baltic seas. These regions expose seaweed cultivation to hostile conditions during storm events, as noted in studies by Wilson (2019) and Kyryliuk (2019). In response to these challenges, the ULTFARMS project is pioneering an innovative submersible grow-out system. This system is designed to allow the submergence of cultivation lines during adverse conditions, optimizing water depths to reduce the impact of current forces while maintaining the essential light conditions for optimal seaweed growth. Additionally, the project encompasses a comprehensive approach, including testing seaweed nursery settings, seeding techniques, and diversification of cultivated seaweed species. Importantly, these efforts extend offshore, with the production of cultivation protocols to enhance success rates. Previous studies have already demonstrated the production potential of Low Trophic Aquaculture (LTA) in Danish waters, with mapping exercises identifying specific areas, including the Samsø site, as having potential for seaweed production. In regions where offshore wind operators are located, the prospects for seaweed cultivation, particularly the red algae Palmaria palmata (Dulse) and sugar kelp (Saccharina latissima), are promising. Notable innovations within this context include the development of seeding techniques tailored for large-scale dulse seaweed production on grow-out nets, along with timing trials for harvesting and extending the growth season, all aimed at enhancing commercial viability. Similarly, within the FINO2 project, a focus on cultivating Baltic Sea-specific seaweed, including red algae Palmaria palmata (Dulse) and Ulva (sea lettuce), presents significant opportunities. The project entails the development of seeding techniques for large-scale dulse production on grow-out nets. Orientation and light regime exposure in submerged seaweed grow-out systems are optimized for the species implemented at the site. Moreover, there is a commitment to adapt systems to the specific conditions of the Baltic Sea, ensuring robustness and scalability. Strategies for highlighting the added value of the product are also being explored.

In the original state-of-the-art design for seaweed aquaculture in the OWF settings of FINO2 and FINO3, there are distinct focuses and objectives at each site. At the FINO2 site, the emphasis is on growing Baltic Sea-specific seaweed varieties, particularly bladder wrack (*Fucus vesiculosus*) and sea lettuce (*Ulva lactuca*). Innovative approaches are being developed, including seeding techniques for large-scale production of *Fucus* on grow-out nets. The orientation and light exposure in the submerged seaweed grow-out systems are being optimized for the specific species in this site. NID, similar to FINO3, is given significant importance. The systems are being adapted to the unique conditions of the Baltic Sea, ensuring their robustness and scalability. Additionally, strategies and marketing techniques are being explored to highlight the added value of the seaweed products, despite potentially higher costs. In contrast, the focus at the

FINO3 pilot site in the North Sea is on seaweed cultivation techniques for seeding and strain development of more profitable species, such as *Saccharina latissima*. Genetic investigations are being conducted to identify suitable strains that can thrive in offshore cultivation conditions. The project aims to examine sound cultivation methods and best practices to enable future industrial seaweed production, contributing to the emerging European Blue Economy. Overall, these designs reflect the site-specific considerations and objectives for seaweed aquaculture. The goal is to optimize production, adapt to local conditions, and contribute to the development of a sustainable and economically viable seaweed industry.

Lastly, an essential component of the project centres on the exploration of seeding techniques and strain development for more profitable seaweed species, particularly Ulva, intended for offshore cultivation. This endeavour involves genetic investigations to identify suitable strains, sound cultivation methods, and best practices. The knowledge generated through these efforts is poised to contribute significantly to the emerging European Blue Economy. Additionally, the project introduces an innovative, cost-effective method for monitoring and analysing toxin levels, which is set to undergo rigorous testing and validation within the site. The current state of seaweed cultivation at the proposal stage reflects a comprehensive approach aimed at optimizing production while mitigating environmental impacts. This approach embraces innovation, adaptability to regional conditions, and a commitment to enhancing the seaweed cultivation industry within the European context.

## 3.2 Advances In SoA

Seaweed LTA designs and technologies have been gaining significant attention in the past few years. Recent studies have focused on advancements of seaweed cultivation methods, on mapping methodologies through remote sensing, and on the potential of seaweed aquaculture to address environmental challenges such as carbon dioxide removal.

Dussan et al. (2023) have reviewed the last two years of research and development initiatives covering aspects such as seaweed supply and logistics, and recent advances and studies on valorisation of cultivated seaweed via biorefining. However, they also highlight challenges in terms of lack of monitoring systems and good growth models consistent with large scale seaweed cultivation.

A second review paper discusses the challenges and opportunities of seaweed aquaculture in offshore environments., The authors identify that the key knowledge gaps are cultivation technologies and suitability to offshore conditions. Moreover, they suggest a research roadmap to inform the advancement of a commercial offshore seaweed aquaculture industry using southern Australian species as case studies (*Visch et al., 2023*). The article also highlights the potential benefits of offshore operations, including minimised environmental impacts and less fouling and grazing due to physical separation from many natural seaweed ecosystems. A systematic review paper by O'Shea et al. (2022) has provided an up-to-date synthesis of evidence on the economic, social and environmental impacts of seaweed aquaculture development in wind farms. The study findings were used to construct conceptual models as a first step to further reduce multi-use setting impact uncertainty. Hurd et al. (2023) highlight new aquaculture initiatives using seaweed to reduce methane emissions in ruminants and for food production. In terms of advancements of seaweed aquaculture monitoring through remote sensing, the study by Runjie et al. (2023) focused on accurate mapping of seaweed farms in offshore China. Planet Scope satellite images were used to obtain a highly accurate map of cultured seaweed in 2018-2019. This approach can be used to replace more conventional monitoring methods and expanded on a larger or global scale.

Several studies have also looked at the ecological value and co-benefit of scaling up offshore seaweed cultivation and sinking it for carbon sequestration. An article explores the legal issues of two different ocean carbon dioxide removal techniques, i.e., offshore carbon dioxide storage and seaweed cultivation under the legal regimes for both climate change and oceans (*Zou et al., 2023*). Luo et al., 2023 have quantified the carbon sink potential of cultivated seaweeds in China, thereby showing the value its ecological value in terms of increasing marine carbon sequestration and resolving offshore environmental issues (*Luo et al., 2023*). Another recent study (*Wu et al., 2023*) has looked at the potential of these macroalgae in offshore aquaculture as an ocean-based carbon dioxide removal method through model simulations, however they also highlighted the potential side effects of large-scale deployment on marine ecosystems and biogeochemistry. A study by Navarette et al. (2021) analysed a potential solution for the problem that in large part of the ocean, large-scale cultivation of seaweed is limited by seasonal or chronic nutrient limitation in the photic zone. They tested a diel depth-cycling approach for the cultivation of Giant Kelp in open ocean regions with nutrient poor surface waters and nutrient rich deeper waters. They used an anchored buoy-elevator system to change the depth of the kelp depending on the time of the day, alternating between ~9 meters below the surface during the day and ~80 meters below the surface during the night. This study performed their experiments in the Southern California Bight for a period of 90 days. Their results showed that the Kelp that was grown at the alternating depths produced four times more biomass than the kelp that was grown under normal conditions. The authors suggest that the depth-cycling solution might also be used to prevent thermal stress. Lastly, Osborne et al. (2023) investigated the microbial community of the seaweed *Macrocystis pyrifera* to identify the key microbial taxa that could be inoculated to improve crop yield in offshore farms.

## 3.3 Overview

- ### Risks

Offshore seaweed cultivation has gained significant attention as a sustainable solution to environmental and economic challenges. While it offers benefits such as carbon sequestration and nutrient uptake, it also comes with known risks. One of the risks associated with offshore seaweed cultivation is its potential environmental impact. While seaweed absorbs carbon dioxide and nutrients, excessive cultivation could deplete localized nutrients, alter water flow patterns, and affect biodiversity. This emphasizes the importance of considering factors like farm scale, species cultivated, and management practices. Extreme weather events pose a threat to offshore seaweed farms. Storms can cause physical damage to farm structures, leading to crop loss. Proper design, engineering, and location selection are vital for mitigating these risks.

Harvesting and post-harvest challenges are additional risks. Harvesting methods, such as mechanical cutting or manual collection is time-intensive and not feasible for large scale applications. Proper storage and transportation are necessary to maintain seaweed quality and prevent spoilage. Employing sustainable harvesting techniques and efficient post-harvest practices can help minimize these risks. Moreover, going offshore poses a whole set of risks related to weather and physical conditions compared to coastal operations. For seaweeds, there is the risk of line breakage and/or entanglement as a result of different wave/current regimes than in coastal areas. On site operations will also be more challenging than in coastal farm sites, and thus visits to check the farm will be very weather dependent and less frequent.

Furthermore, regulatory and legal considerations add complexity to offshore seaweed cultivation. Compliance with regulations and obtaining permits can be challenging, particularly in jurisdictions where the industry is still developing. Understanding and adhering to relevant environmental impact assessments and aquaculture licenses is crucial for a sustainable and legally compliant operation.

In conclusion, offshore seaweed cultivation offers great potential for sustainable solutions. However, it is important to address the known risks associated with it. By implementing proper management practices, conducting ongoing research, and staying informed about industry developments, the offshore seaweed industry can work towards minimizing risks and maximizing the benefits of this innovative form of aquaculture.

- ### Challenges

Some of the known challenges related to seaweed offshore cultivation depend in part on the local environmental conditions at the pilot sites. Offshore algae aquaculture in the Baltic Sea faces several challenges due to the unique conditions of this region. The Baltic Sea presents complicating saline gradients,

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which can be detrimental to the growth and development of algae. Being a transition zone between the saline North Sea and the brackish Baltic Sea, low and fluctuating salinities in the inner Danish waters (at the Anholt pilot) will potentially cause some challenges for the growth performance of the seaweed. The varying levels of salinity make it difficult to maintain optimal conditions for algae cultivation, as different species have different salinity requirements. Although the chosen species can potentially tolerate these conditions, there is the risk that biomass production potential will be affected and thus, harvest yield will be lower than expected from other farm sites. Moreover, the offshore conditions in the Baltic Sea pose additional obstacles. The region experiences long sea routes. which can increase transportation costs and logistical complexities. The typical Baltic Sea conditions, characterized by lower salinity, shorter waves, and shallower waters, create a distinct environment that demands careful consideration when designing offshore algae cultivation systems. In addition to these challenges, bad weather conditions, winter ice, and the general travel distance further compound the difficulties of offshore algae aquaculture in the Baltic Sea. The severe weather conditions that occur in the region can disrupt operations and pose risks to the infrastructure and personnel involved in the cultivation process.

Furthermore, the North Sea presents even more hostile physical conditions that need to be taken into account. The strong currents and rough seas can pose challenges for the anchoring of offshore infrastructure, requiring robust and secure anchoring systems to ensure the stability and safety of the aquaculture facilities.

Lastly, fouling, the accumulation of unwanted organisms on submerged surfaces, is a significant concern in offshore algae aquaculture. Fouling can negatively impact the growth and productivity of algae, as it competes for space, nutrients, and light. Effective fouling management strategies and regular maintenance are necessary to mitigate the adverse effects of fouling on the algae cultivation systems.

Offshore algae aquaculture in the Baltic Sea faces multiple challenges, including complicating saline gradients, harsh offshore conditions, long sea routes, low salinity, bad weather conditions, winter ice, hostile physical conditions, anchoring difficulties, and fouling. Most of these challenges exist also in the North Sea in an even harsher environment, but with more consistent salinity. Overcoming these challenges requires innovative engineering solutions, robust infrastructure, and efficient management practices to ensure sustainable and successful offshore algae cultivation in these regions.

- **Potential solutions**

ULTFARMS aims to mitigate or reduce some of the risks and challenges described above. Additionally, there is an overall ambitions to increase the productivity and ecological balance of such systems, particularly when considering the scale to a commercial level of use. In order to do so, multiple solutions will be implemented at the various pilots sites which are implementing seaweed cultivation, both in the Baltic and the North Sea.

Among the key initiatives, the project is devoted to refining seeding techniques, aiming to enhance the establishment of seaweed populations, thereby ensuring a robust foundation for growth. Additionally, with commercial partners, ULTFARMS will aide and make use of the development of algae strains tailored to the demands of offshore farming holds promise for optimizing production. The production potential of dulse seaweed will be tested at multiple sites, but notably those in the Baltic Sea as it has proven to be a species with good potential to cope with low and even more importantly fluctuating salinity. Furthermore, trials will be conducted for this species to be seeded on nets in comparison with traditional line seeding to identify means to improve the area-specific harvest yield of the species. This will imply the development of seeding techniques for larger scale production in the hatchery.

One of the project's hallmark achievements is the development of an innovative submersible seaweed long-line system, representing a significant leap in efficient cultivation practices. Concurrently, improvements in aquaculture infrastructure further enhance seaweed growth and protection. The applicability and effectivity of semi-submersible systems, either through an automation system based on forecasts and monitoring or a manually induced system will be implemented . This includes trialling of new submersion systems as well as implementing proven system designs as well.

The project integrates affordable monitoring techniques that enable the continuous assessment of seaweed growth and environmental conditions. This commitment is further strengthened by the inclusion of the HiSea service, providing access to precise oceanographic information to inform decision-making processes. Improvements to observation program and the inclusion of new or emergent solutions to determine their effectivity over traditional monitoring is also implemented with the project. Camera-based observation programs will be implemented before the farm setup as well as after/during to assess the potential effects on biodiversity of a farm with seaweed and mussel cultivation. Of note are low-cost methods to monitor proxies for toxins which can cause issues for the growth and suitability of later uses of the seaweeds as well. To ensure meticulous monitoring, scanning sonars and tilted transducers are deployed on Unmanned Surface Vehicles (USVs), providing detailed insights into the seaweed farm's dynamics. ULTFARMS places a strong emphasis on monitoring the forces, movements, and depth variations within the seaweed farm through a sophisticated network of sensors. The integration of sensor data interpretation with existing environmental measurements allows for comprehensive analysis. The project diligently measures forces with load cells to monitor seaweed farm infrastructure, transmitting sensor data remotely and in real-time for continuous monitoring. Webcams and GPS trackers are utilized to promptly detect system breakage or malfunctions, bolstering the system's resilience. Furthermore, ULTFARMS leverages AIS Buoys to enhance monitoring and tracking capabilities, ensuring a robust and reliable seaweed cultivation system. These monitoring elements, including cameras, samples, and modelling efforts will be combined in the HiSea data platform to allow for a more effective aggregation of the data elements into a singular space both to aid in the development and application of alerts and decision support tools. This will also aide the the dispersal and sharing of the information at the completion of the project.

In the pursuit of sustainability, ULTFARMS explores the feasibility of harnessing on-site renewable energy sources, not only reducing the carbon footprint but also curbing operational costs. This holistic approach extends to the design of seaweed grow-out systems, which are meticulously crafted to achieve specific orientation and light exposure conducive to optimal growth. With a dedication to nature-inclusive design principles, the project strives to promote biodiversity and ecosystem health within the seaweed cultivation environment. Innovative monitoring and automation techniques are employed to streamline operations, with the potential to involve fishermen in monitoring activities, fostering a collaborative approach.

To safeguard against erosion and foster marine species colonization, nature-inclusive scouring protection materials are assessed and included in a selection of sites. Video monitoring systems and acoustic sounders augment our knowledge of local species diversity and behavior. In addition, the project undertakes an assessment of the ecological benefits associated with artificial reef structures through standardized protocols. Evaluating biodiversity on hard substrates employs advanced identification techniques, enriching our understanding of local species diversity. The types of nature inclusive design elements being considered in the project, and to what degree these can be assessed as benefiting nature when compared to baseline conditions within the pilot sites is also a strong point of concern for the project, with an ambition to produce guidelines and preliminary evaluation criteria for such designs.

In essence, the ULTFARMS project embodies a holistic approach to seaweed cultivation, blending innovative techniques, sustainability, and rigorous monitoring to pave the way for a resilient and prosperous future in Low Trophic Aquaculture within Offshore Wind Farms. The ULTFARMS project is at the forefront of implementing innovative solutions to tackle challenges and mitigate risks associated with LTA) of Seaweeds in OWF. Through advancements in seeding techniques, algae strain development, cost-effective monitoring methods, renewable energy utilization, and nature-inclusive design, the project aims to promote sustainable and efficient seaweed cultivation. By integrating cutting-edge technologies such as monitoring and automation techniques, artificial reef structures, advanced imaging systems, and optimized aquaculture infrastructure, the project strives to optimize farm operations, enhance biodiversity, and ensure the safety and productivity of seaweed crops.

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# 4. Mussel aquaculture in OWFs

Mussel aquaculture has a long history of operation and is being commercially exploited on a global scale, and has continued to increase in the global context with approximately 94% of global mussel production stemming from aquaculture activities (Avdelas, L. et. al , 2020). However, production has begun to fall in the European Union since the 1990's, Avdelas et. al. have cited potential causes of this decline to include diseases, lack of mussel spat for seeding, and decreased profitability from production costs within the European domain. Therefore, novel and more cost-effective methodologies of mariculture for these species, alongside an ecologically friendly and restorative approach may enable a rebound in this sector to better supply the EU's domestic demand for mussels and decrease the volume of imports from foreign markets. To such ends, Van den Burg et al. (2017) addresses potential business cases for mussel aquaculture in offshore wind farms in the Dutch North Sea, demonstrating through such cases that farming mussels in windfarms such as Borssele, also one of the ULTFARM pilot cases, can be economically feasible. Such an application would be possible using existing long-line culturing of mussels, an established technique, but adapting specific components to make it compatible for off-shore exposed North Sea conditions.

Furthermore, LTA developments for mussels in terms of designs and technologies have gained significant attention in recent years due to their potential to address sustainability challenges in the aquaculture industry. LTA refers to the cultivation of species lower on the food chain, such as mussels, seaweed, and other filter-feeding organisms, which have minimal environmental impact and high nutritional value; offshore settings provide ample space and favorable conditions for LTA operations. Several innovative designs and technologies have been developed to support LTA of mussels in offshore environments. These advancements aim to optimize production, enhance biosecurity, and improve operational efficiency. One of the key technologies employed is the use of offshore floating systems, which can be either longline or raft-based. These systems allow mussels to be cultivated in open waters, benefiting from strong currents and nutrient-rich marine environments. Already demonstrated in pilot cases are various configurations of longline systems, including horizontal and vertical setups. Horizontal longlines consist of a series of parallel ropes suspended between buoys, while vertical systems use ropes hanging from a submerged mainline. These designs enable efficient space utilization and facilitate scalability. Additionally, proto-types for automated monitoring systems, such as underwater cameras and sensors, are integrated into these systems to monitor growth, health, and environmental parameters.

In terms of TRL, mussel LTA designs and technologies are at varying stages of development. Some systems, such as horizontal longlines, have already reached high TRL levels, with successful commercial deployments in various locations worldwide. These systems have demonstrated their ability to withstand offshore conditions and deliver substantial yields to a certain extent. Vertical longline systems and advanced monitoring technologies are still undergoing refinement and optimization, with TRL levels ranging from medium to high.

The application of LTA in offshore settings offers numerous potential benefits. Firstly, it stands to potentially reduce the ecological impact associated with traditional aquaculture practices, as mussels efficiently filter and extract excess nutrients from the water, promoting water quality improvement. Additionally, spreading the impact of such aquaculture over a wider extent instead of high concentrations of activities in near shore environments, which are also critical for wildlife and biodiversity preservation can enable substantial production capacities with a distributed impact within ecological carrying capacities. Furthermore, LTA operations when combined in a multi-use setting can minimize conflicts with other marine activities, as they are located farther offshore and combine their footprints with additional activities. Finally, the cultivation of mussels in offshore environments allows for the expansion of the aquaculture sector, providing opportunities for sustainable food production and economic growth. The advancements in LTA of mussels contribute to the sustainable growth of the aquaculture industry, stand to aid in environmental challenges, and can help Europe lower it's importation of blue biomass thereby increasing it's domestic food security.

## 4.1 Original State of Art (Design SoA)

Of the six pilots in ULTFARMS, 5 will be addressing mussel LTA as listed in Table 1.1. Each case is testing an adapted system design, unique to the location and requirements (either physical, or bio-geo-chemical related) in order to optimize the configuration, growth, and health of the farmed stock and compensate for the exposed off-shore conditions through unique anchoring design, a submersible platform, or submersible lines.

Of the 2 German pilots, Fino 2 and 3, the test site Fino3 is an innovative project that aims to explore and advance the state-of-the-art mussel cultivation techniques. It serves as a testbed for the development and optimization of sustainable and commercially viable methods for not only mussel farming in offshore environments. The project is led by FINO 3 partners, who possess extensive experience in licensing projects, establishing connections with relevant agencies, and understanding the German market.

The cultivation of mussels in offshore environments presents numerous advantages. Offshore areas provide ample space and favorable conditions for mussel growth, ensuring optimal water quality and nutrient availability. Furthermore, the cultivation of mussels contributes to the enhancement of marine ecosystems by filtering and purifying seawater, promoting biodiversity, and creating a habitat.

The Test site Fino3 acts as a proving ground for the commercial uptake of mussel cultivation, particularly in combination with other activities close to offshore wind energy production. A comprehensive business plan has been developed, outlining the potential for a multi-use approach that integrates LTA and offshore wind energy production.

The project remains aligned with the latest technological advancements, market dynamics, and regulatory frameworks. The involvement of FINO 3 partners and their expertise in project licensing and engagement with relevant agencies guarantees a thorough understanding of the regulatory landscape and maximizes the project's chances of success.

By leveraging the experience and knowledge gained from the Test site Fino3, the commercial uptake of mussel cultivation and its integration with offshore wind energy production can be accelerated. This pioneering initiative has the potential to revolutionize sustainable aquaculture practices, foster environmental conservation, and contribute to the growth of the renewable energy sector.

The Dutch pilot of Borssele is a wind park development located about 55 kilometres from the Port of Vlissingen, Netherlands consisting of four major areas, of which sections III and IV are owned and operated by the consortium Blauwwind. The multiuse planning for these two areas includes a section dedicated to the integration of aquaculture within the wind park. This is the location where the Submersible Mussel Farm (SMF) is planned to be deployed within the project activities.

The Borssele pilot aims to combine the various sensor monitoring information into models to predict the nutrient removal and ecological impact of mussel farming at commercially viable scales. Remote and in-situ monitoring technologies are being used by pilot operators to feed into a database system enabling risk analysis for aquaculture. Due to densely positioned mussel lines, monitoring of the forces acting upon the structures, degradation of components and collecting additional data on mussel growth on the open sea floor in offshore conditions is critical to feeding activities.

## 4.2 Advances In SoA

A number of recent advancements and research related to mussel aquaculture have centred on exploring the potential for coexistence between offshore mussel farms and wind farms, reflecting a growing body of research and proposed solutions. Various group been developing potential synergies, normally focusing on national or regional implementation options; Nordic Energy Research has played a notable role in this discourse in the Nordics, publishing a report that delves into the concept of coexistence within Nordic offshore wind farms. Coexistence, as defined in the report, entails harmonizing various maritime activities, including fisheries, shipping, military operations, aquaculture, tourism, and nature preservation, all occurring within the same geographic area. The overarching goal is to minimize negative impacts while optimizing collective benefits. The report sheds light on opportunities and risks associated with Nature-Inclusive Design (NID), particularly concerning seabed restoration and conservation. NID, as described by the authors, encompasses options that can be integrated into or added to anthropogenic structures to enhance ecological functioning. Both coexistence and NID emerge as pivotal concepts for safeguarding the seabed and marine biodiversity. The report showcases various NID options, ranging from "fish hotels" to optimized cable designs and scour protection layers, exemplifying the innovative approaches that can be adopted. These NID options have made some of the most notable changes since the project's inception; Hermans et al. (2020) have contributed to this evolving landscape by compiling a catalogue of NID options tailored to offshore wind infrastructure, with a specific focus on the Dutch North Sea. The insights derived from their work hold the potential for replication in other regions, promoting ecological sustainability across offshore wind projects worldwide.

In addition to these developments, there is a growing recognition of the local effects of offshore wind farms and their interaction with global climate change. Voet et al. (2021) have undertaken a study aimed at quantifying the ecophysiological effects of ocean warming and acidification. Their research also seeks to estimate and compare the cumulative clearance potential of suspended food items by epifauna, including blue mussels, colonizing offshore wind farm foundations. The findings underscore the far-reaching consequences of increasing sea surface temperatures and declining surface water pH levels on marine organism survival, productivity, and growth. These studies illuminate the intricate relationship between offshore wind farms and the surrounding environment, offering valuable insights for industry stakeholders and policymakers as they navigate the challenges posed by climate change and its impact on marine ecosystems. In summary, recent advancements in mussel aquaculture emphasize the importance of coexistence, Nature-Inclusive Design, and the ecological ramifications of offshore wind farms in the context of broader climate change considerations. These designs, applications, and evaluations are under consideration within the ULTFARMS project, with a consolidated review of Nature Inclusive Design trials and their impacts expected to be produced by the specific NID working group at the end of 2024.

The near-field and bay-scale effects of offshore mussel farms on epibenthic macrofaunal communities has also has a number of developments. Sean et al. (2022) considered mussel  had an influence on benthic communities, with some species (crabs, northern moon snails, sea stars and American lobsters) being more abundant within farm sites than outside. Mussel farms could serve as ecological traps for the species that gather within them. However, the long-term effects are still unknown. *Guillou et al. (2023*) suggest that offshore mussel cultivation may be a viable alternative strategy for aquaculture development. The study investigated the differences in performance (quantity and quality) between nearshore and offshore blue mussel (*Mytilus edulis*) farms based in Québec. The offshore environment offered improved water quality, oxygen, and thermal conditions compared to nearshore areas, however it also presented challenges such as lower nutrient availability and a higher risk of exposure to toxic phytoplankton, diseases, parasites and pesticides. A number of smaller studies have also addressed the potential ecological effects of mussel aquaculture but an overarching reanalysis has not been found for the most recent period and therefore additional or new information under such an approach ahs not been recently revised or realized.

Research is being continually conducted to enhance productivity and maximize production efficiency, all while minimizing the environmental footprint of mussel aquaculture. One such study by Landmann et al. (2021) developed new designs and tests to obtain more efficient mussel farm structures. Tests were made on mussel dropper lines to evaluate the best hydrodynamic coefficients (drag and inertia coefficients) according to waves and currents, to minimize losses and improve mussels' longevity. Two different kinds of mussel were tested, the blue mussels (Mytilus edulis) and the green-lipped mussels (Perna canaliculus). They have found that a larger characteristic diameter of the live and surrogate dropper lines provides better hydrodynamic coefficients. Further research is underway to investigate the impact of soft growth and surface roughness on the hydrodynamic parameters of mussel dropper lines.

In terms of monitoring and operational activities, Italian researchers led by *Tassetti et al. (2022*) developed innovative forms of Augmented Reality (AR) technology. This new technological support simplifies everyday tasks for farmers, but also provides real-time visual access to the entire farm, thereby offering valuable information on weather conditions and other factors. In a case study conducted in an offshore mussel farm in the Adriatic Sea, the researchers used object detection videos and a multibeam echosounder to geo-locate buoys in real time and make observations on fixed mussels that were not visible through onboard cameras. Furthermore, *Rampal et al. (2023*) have developed a forecasting model of mussel meat yield based on the relationships between non-local Sea Surface Temperature (SST) and observed yield data,. The SST anomalies alone accounted for 60% of the seasonal variance in mussel meat yield anomalies from 1997-2005 and 42% from 2015-2019. This forecasting model can be a valuable tool for mussel farmers, allowing them to manage and make informed decisions based on anticipated mussel yields.

These and other studies have been referenced in the design and deployment elements of the ULTFARMS project and are noted in the relevant deliverable on preliminary design and operational elements, namely task and deliverable 3.1

## 4.3 Overview

- **Risks**

Offshore mussel cultivation offers significant potential for meeting the growing demand for sustainable seafood production. However, like any farming endeavor, it is not without risks. In order to effectively operate offshore mussel farms, it is crucial to be aware of and manage these risks. This section will discuss some of the known risks associated with offshore mussel cultivation, including logistical risks, recruitment uncertainties, farm structure integrity, and cost volatility. An overview is provided below:

- Logistical risks: Logistical challenges are inherent in offshore operations due to the remote nature of the farming sites. Transportation of equipment, supplies, and personnel to and from the farm can be more complex and time-consuming compared to nearshore locations. The logistics of maintaining and servicing offshore farms require careful planning and coordination to ensure smooth operations.
- Risk of material and biomass Loss: Offshore farms are exposed to heavy storm events, which pose a significant risk to the farm's infrastructure and the mussels themselves. Strong winds, high waves, and turbulent waters can cause material and biomass loss, potentially resulting in economic losses for the operators. Mitigation measures such as robust mooring systems and durable farm structures can help reduce this risk.
- Risk of entanglement of mussel lines: Offshore farms utilize long lines or ropes to suspend mussel nets in the water column. However, these lines can become entangled with debris, fishing gear, or other marine organisms, posing a risk to the farm's productivity and also to marine birds and mammals. Regular monitoring and maintenance are required to identify and mitigate entanglement risks promptly.
- Recruitment uncertainty: Recruitment of wild mussel spat (larvae) in offshore conditions is unpredictable in terms of both periodicity and annual replicability. There is a risk of poor recruitment or settlement timing that may not synchronize with the setup schedule with the site. This uncertainty can impact the farm's production and necessitate adjustments in management strategies to maximize spat collection.
- Insufficient engineering specifications: In some cases, operators may not adhere to sufficient engineering specifications when constructing offshore farms. This can result in the deterioration or loss of the farm's infrastructure, jeopardizing its stability and functionality. Compliance with engineering guidelines and regular maintenance are crucial to ensure the longevity and effectiveness of the farm.

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- Sea safety risks: Operating offshore entails higher sea safety risks compared to nearshore locations. Increased exposure to open waters requires operators to adapt to enhanced safety measures and redundancies. This includes robust safety equipment, well-trained personnel, and emergency response protocols to ensure the safety of workers and the farm's assets.
- Cost volatility: The costs of offshore mussel production are influenced by various factors, including fuel costs. Sailing time for maintenance and harvesting during periods of volatile energy rates can significantly impact the overall production costs. Operators need to carefully manage and forecast energy costs to minimize financial risks associated with fuel price fluctuations.
- Farm structure integrity: Offshore farms are exposed to high energy regimes characterized by strong currents and waves. These environmental conditions pose a risk to the integrity of farm structures. Lines can become wound, twisted, or tangled, resulting in crop loss, while buoys under snap tension can be lost, compromising the structure's stability. Regular inspections and proactive maintenance are essential to mitigate these risks.

With increased production costs and variable growth performance potentials compared to nearshore sites, offshore farms are expected to operate on narrower profit margins. Consequently, they are more vulnerable to volatility in cost inputs, such as labour, equipment, and fuel. Operators, and particularly in the case of these pilot and testing deployments as are planned within the ULTFARMS project, must carefully monitor and manage production costs to ensure the economic viability of their offshore mussel farms. However, it is essential for operators to be aware of the known risks associated with this method. By effectively managing logistical challenges, recruitment uncertainties, farm structure integrity, and cost volatility, operators can maximize the potential of offshore mussel cultivation while minimizing potential adverse impacts, key elements to making the solutions developed within ULTFARMs commercially viable and attractive for implementation.

## • Challenges

Offshore mussel cultivation in the Baltic and North Sea presents several known challenges and risks due to the unique environmental and regulatory conditions in these regions. One of the primary challenges is the complicating saline gradients in the Baltic domain. The Baltic Sea has varying salinity levels, which can affect the growth and survival of mussels. Mussels thrive in a certain range of salinity, and the fluctuating levels in the Baltic Sea can pose difficulties for their cultivation.

Harsh offshore conditions in both the Baltic and North Sea also pose challenges. These conditions include strong winds, rough seas, and extreme weather events. These factors can impact the structural integrity of offshore infrastructure and the overall success of mussel cultivation operations.

Another challenge is the long sea routes that need to be traversed to transport the mussels from the cultivation sites to the market. This transportation process can be logistically complex and expensive, requiring careful planning and coordination. The typical Baltic Sea conditions, such as low salinity, shorter waves, and shallower waters, further add to the challenges. As mussels require specific water parameters for optimal growth, and the Baltic Sea conditions may not always be conducive to their cultivation, the potentials in yield and productivity will be of significance and importance in the development of such activities within this domain. The outcomes from ULTFARMS will pay particular attention to the modelling and prospective yields within this area to best define the potential from a commercial standpoint. Additionally, the absence of significant tidal currents can affect the availability of nutrients and food supply for the mussels, further complicating the yield projections and commercial viability.

The management procedures for offshore mussel cultivation in the Baltic and North Sea are also challenging. Fractionated regulatory frameworks and sectorial focuses on licensing systems can create complexities and delays in obtaining the necessary permits for cultivation operations. These administrative hurdles can hinder the development and expansion of offshore mussel farms. Moreover, the Belgian part of the North Sea presents hostile physical conditions, making the anchoring of offshore infrastructure challenging. Strong currents and rough seabed conditions can affect the stability and longevity of the infrastructure, requiring additional measures to ensure its integrity.

Finally, fouling, which refers to the accumulation of organisms on the infrastructure surfaces, is a risk in offshore mussel cultivation. Fouling can lead to decreased water flow, hindered growth, and increased maintenance costs. Regular cleaning and maintenance are necessary to mitigate the negative impacts of fouling. To address these challenges and risks, ongoing research and innovation are crucial. The development of specialized cultivation techniques, such as integrated multi-trophic aquaculture systems (Lehtonen, 2019), can help mitigate the effects of varying salinity levels and optimize resource utilization. Improved anchoring technologies and infrastructure design can enhance the resilience of offshore farms against harsh conditions. Additionally, collaboration between regulatory bodies and stakeholders is necessary to streamline licensing procedures and foster sustainable growth in offshore mussel cultivation.

- ### Potential solutions

The ULTFARMS project addresses the challenges and risks associated with offshore mussel aquaculture in OWFs by implementing and testing a range of innovative solutions. One of these solutions is the use of submersible systems for offshore mussel farming, which provide protection from extreme weather conditions and reduce visual impact.

Different cultivation technologies are explored within the project, including longline systems (blue mussels), droppers (algae), baskets (oysters), and lanterns

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(oyster), offering various approaches to optimizing growth and production. A discrete observation program is implemented to monitor the mussel farms, collecting data on growth, health, and environmental impacts to better understand their behavior and performance. To ensure efficient and sustainable management practices, the project focuses on developing cost-effective monitoring techniques. These techniques assess water quality, nutrient levels, and ecological impacts. HiSea services, utilizing Earth observation and satellite data, provide accurate and timely information about water quality and environmental conditions to support decision-making.

The project also emphasizes the utilization of renewable energy produced on-site, if possible and feasible directly from the offshore wind farms, to power the mussel aquaculture systems, promoting sustainability and reducing dependence on external energy sources. Efforts are made to repurpose waste shell material from mollusc production as smart materials and feed for livestock, minimizing waste and maximizing resource utilization. Nature-inclusive design principles are followed, considering the needs of various species and habitats to minimize negative impacts and enhance the overall ecological value of the mussel farms.

Various sensor monitoring information shall be combined into models that predict nutrient removal and ecological impacts of mussel farming at commercially viable scales, aiding decision-making and ensuring sustainable practices. Remote and in-situ monitoring technologies shall collect data and feed it into a database system, enabling real-time monitoring and risk analysis for aquaculture operations. Novel sensor applications, such as classical load cells, accelerometers, and depth sensors, can be used within the backbone construction of the mussel farms to provide valuable data on structural integrity and performance. Sensor data collected from the farms are linked with existing environmental measurements, obtained via measuring buoys and satellite images, to enhance the understanding of ecological impacts and inform decision-making. Scanning sonars and multibeam sonars installed on Unmanned Surface Vehicles (USVs) can be used to collect data on water column characteristics, substrate composition, and potential habitat effects. The "artificial reef effect" of the mussel farms could be assessed through a standard monitoring protocol.

In terms of infrastructure, depth-adjustable submerged mussel farm platforms are planned to adapt to varying water depths and optimize environmental conditions for mussel growth. An example of such system is the depth-adjustable Submerged Mussel Farm Platform will be implemented in the Dutch Northern Sea. This system utilizes a semi-submersible platform as a central point from which the cultivation longline runs. This central platform serves as the connector point and remains almost fully submersed to guard the aquaculture lines from the harsh environment. The unique line deployment system to be implemented in this configuration is relatively denser than many existing configurations.

Biodiversity associated with the mussel farms shall, if possible, be assessed using a combination of morphological identification and metabarcoding techniques. Nature-inclusive scouring protection materials can be utilized to minimize the impact of farm structures on the seabed while providing habitat and protection for various species.

Overall, the ULTFARMS project utilizes a comprehensive array of solutions to tackle challenges and risks, supporting the successful implementation of offshore mussel aquaculture in OWFs. Through innovation, data-driven approaches, and nature-inclusive designs, the project aims to optimize mussel farm performance, minimize environmental impacts, and maximize resource utilization.

# 5. Connecting to Pilot Designs & moving Forward

## 5.1 Dutch

The Dutch pilot aims to integrate various monitoring technologies to assess mussel performance and the ecological impact of mussel farming at commercially viable scales. In addition, this pilot will implement a unique line deployment system, which is notably denser compared to many existing configurations.

The pilot also aims to increase the use of renewable energy throughout the entire value chain of low trophic aquaculture production. This includes direct on-site energy consumption. Moreover, this pilot will aim for the establishment of an artificial reef below the mussel farm, thereby promoting biodiversity enhancement. Technical monitoring of water quality plays a crucial role in providing indicators for toxic phytoplankton, which can significantly affect both the viability of mussel production and the well-being of end consumers of the harvested mussels.

Challenges in implementing a full-scale Submerged Mussel Farm (SMF) with high-density mussel lines include the need for new management procedures to avoid delays, navigating complex regulatory frameworks, and sector-specific licensing systems. Special attention is given to structural planning, synergies, and the potential for on-site energy use. Monitoring and automation efforts within the Borssele pilot aim to integrate sensor data into predictive models for nutrient removal and ecological impact assessment at commercially viable scales. Remote and in-situ monitoring technologies feed data into a centralized database, facilitating risk analysis for aquaculture operations. Given the densely positioned mussel lines, monitoring forces on structures, component degradation, and collecting data on mussel growth in offshore conditions are critical aspects of these activities.

To address the challenges posed by offshore mussel farming in the Dutch Northern Sea, an innovative approach involves the implementation of a depth-adjustable Submerged Mussel Farm Platform. This system utilizes a semi-submersible platform as a central point for deploying cultivation longlines, which are kept submerged to protect them from the harsh environment. This configuration features a relatively denser line deployment system compared to existing configurations.

## 5.2 Belgian

The Belgian Pilot consists of the nearshore Blue Accelerator Test Platform and an offshore site situated within the windfarm, Belwind, operated by Parkwind. The Belgian pilot aims to advance the TRL of all three types of aquaculture outlined in the previous chapters in the context of offshore LTA. Offshore testing of oyster and seaweed aquaculture is currently underway at the Belwind site as part of the ongoing UNITED project. However, demonstration of mussel cultivation in Belgian waters has only been carried out in a nearshore context (Edulis project 2016-2020). The ULTFARMS Belgian pilot aims to build off the lessons learned in these previous projects and to integrate mussel cultivation knowledge from German partners to address challenges in new and innovative ways.

Some of the major challenges of implementing oyster, seaweed and mussel aquaculture at the offshore Belwind site include hostile physical conditions and prevalence of fouling organisms. To address the logistical challenges of working in a high energy environment, novel applications of load cells, accelerometers, and depth sensors on the backbone structures will be developed. Data from these sensors will be used in tandem with existing environmental measurements from weather buoys and satellite imagery to monitor physical and environmental conditions at the offshore site. This will support sea mission planning for maintenance and harvesting.

In order to protect the oyster and mussel cultivation systems from the most intense wave energy near the surface, the longline backbone has a unique sub-surface design. Likewise, a novel submersible longline system is being developed for seaweed aquaculture in collaboration with the industry partner, Impact9. This system aims to keep seaweeds closer to the surface to optimize light availability under normal conditions, and to submerge the longline to a safer depth under storm conditions. Combining this design with monitoring data and telemetry would allow the depth of the seaweed longline structure to be controlled remotely in accordance with expected environmental conditions.

Monitoring of the fouling community and "artificial reef effect" associated with OWFs will be necessary to understand implications for non-indigenous species and consequent changes in food web structure. To this end, innovative methods such as metabarcoding will be assessed in relation to traditional sampling methods. In addition to monitoring and characterizing the fouling community, the Belgian Pilot aims to test new mechanical designs to actively reduce and prevent fouling on aquaculture structures. Through design and testing of novel methods, the Belgian pilot aims to address critical challenges to offshore LTA and advance the technological readiness level of these systems in the Belgian part of the North Sea from TRL 6 to TRL 8.

### 5.3 German

The German Pilot comprises two pilot sites: FINO3, situated in a remote offshore location 80 km north of Helgoland in the North Sea, and FINO2, located in a distant area in the Baltic Sea. Both pilot sites are in close proximity to OWF. While blue mussel and algae cultivation have already been tested at FINO3 under the UNITED Project, no LTA has been conducted at the FINO2 site. Therefore, the primary focus in ULTFARMS lies within the FINO3 site at aiming to improve and expand upon the knowledge gained. This involves refining and enhancing the cultivation techniques for blue mussels and Saccharina latissima algae, as well as integrating the experiences of Belgian partners in oyster growth. The test site FINO3 is equipped with a remote monitoring system that utilizes the existing FINO3 infrastructure to transmit data. Additionally, a novel detection technique for potential toxic micro-algae blooms, which could spoil mussel harvests, will be tested and installed at FINO3.

Due to different environmental conditions, particularly lower salinity levels in the Baltic sea, mussel cultivation is not feasible in the FINO2 pilot site. Since no prior tests or experiences with LTA have been carried out at FINO2, the primary focus will be on testing and establishing an algae cultivation system. Initially, emphasis will be placed on the *Ulva* sp algae, but other relevant species suitable for cultivation under low salinity conditions will also be explored. Furthermore, remote monitoring and the incorporation of a nature-inclusive design will be addressed at the FINO2 site. However, considering that aquaculture is being established at this location for the first time, the expected Technology Readiness Level (TRL) will be lower compared to the FINO3 site.

### 5.4 Danish

The Danish pilot comprises two pilot sites, Anholt and Samsø, both located in the Baltic Sea. The pilot aims to adapt existing and emerging LTA technologies so that they can endure the offshore conditions in the Baltic Sea. In addition, the pilot aspires to understand the production potential of commercially viable mollusc and seaweed species under the complex saline gradients that exist in this region. The physical forces at the Samsø site are less challenging than those at the Anholt site. Given the different conditions, the Samsø site will be used to deploy existing mussel cultivation techniques to test them in the Baltic Sea, while the Anholt site will be used to test new techniques, such as a submersible cultivation system. The Anholt site has a large focus on monitoring: system monitoring, biomass monitoring and environmental monitoring. [...]

## 6. Summary and Conclusions

This deliverable reported on task 10.1 of ULTFARMS: "Review the state-of-the-art recommendations & challenges". The objective of this task is to revise the current

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state of the art for offshore aquaculture in the context of oysters, seaweeds, and mussels since the conception and writing of the proposal.

Several new studies have emerged in the past few years and some commonalities were found across the three aquaculture practices. First, there have been developments in terms of new methods, technologies, and approaches to improve cultivation, species detection and farm operational monitoring. Experimental studies found an increase in mussel growth performance with offshore cultivation, and a positive influence of mussel aquaculture on local benthic community abundance, although the long-term effects are still unknown. Second, there has been further integration of remote sensing and modelling in aquaculture practices, in terms of mapping, site selection, and bioenergetics modeling to optimize production and improve decision-making processes. Lastly, some studies looked at the potential of aquaculture to mitigate environmental issues related to climate change, as in the case of carbon dioxide removal by seaweed. Recent articles also highlight coexistence and NID as crucial concepts for the preservation and restoration of the seabed and of marine biodiversity.

Although offshore cultivation offers advantages in terms of space and can lead to higher productivity, some known risks and challenges are present. For instance, offshore physical conditions are generally harsher and more adverse for aquaculture, the complicating salinity gradients do not allow some of the species to grow, and logistic challenges are present due to the remote nature of the farming sites. While many of the risks and challenges are shared across oyster, mussel, and seaweed cultivation, not all pilots will be dealing with the same challenges, and the same solutions might be used to address a different challenge. For instance, both the Dutch and Belgian pilots will implement innovative semi-submersible platforms for cultivation. However, the Belgian pilot will use this system to deal with the trade-off between light availability and safety during storms for seaweed, whereas the Dutch pilot will keep the platform almost fully sub-surface to protect mussels from the strong and adverse offshore conditions in the Dutch North Sea.

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## 8. Annex I

*Table 8.1: Technology Readiness Level (TRL) scale definitions as defined in the Horizon Europe - Work Programme 2021-2022 - General Annexes (European Commission, 2022)*

| TRL level | Definition |
|---|---|
| 1 | Basic principles observed |
| 2 | Technology concept formulated |
| 3 | Experimental proof of concept |
| 4 | Technology validated in lab |
| 5 | Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| 6 | Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| 7 | System prototype demonstration in operational environment |
| 8 | System complete and qualified |
| 9 | Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) |