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REPORT ON TECHNICAL ASSESSMENT AND VALIDATION

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Abstract	The technical assessment and validation of multi-use offshore aquaculture systems highlights various factors that contribute to their overall sustainability and efficiency. Generalised benefits encompass optimised ocean space utilisation, biodiversity promotion, economic diversification, and environmental sustainability. Costs, avoided damages or loss, and

	<p>environmental benefits are evaluated across different pilots. Uncertainties and robustness are crucial considerations to address challenges and ensure successful implementation. Flexibility plays a vital role in optimising resource utilisation and adaptability. Policy cohesion is essential for aligning with regulations, and support is required for financial, research, policy, and stakeholder engagement aspects to foster adoption. Operationalising these systems requires site selection, tailored design, effective management, collaboration, knowledge sharing, and continuous research. Understanding these aspects enhances the feasibility and integration of multi-use offshore aquaculture systems in coastal and offshore environments.</p>
<p>Keywords</p>	<p>Implementations, costs, environmental benefits, uncertainty, robustness, flexibility, policy cohesion</p>

HISTORY OF CHANGES

<p>VERSION 2.0</p>	<p>December 2023</p>	<p>D8.1 (version 1.0) was submitted in September 2023 without input from the Belgian pilot. A short explanation for this is provided in the technical report (and D10.7). In this document (version 2.0), the missing information has been added. Specifically, the input from the Belgian Pilot in Chapter 4.3 and additions with regard to the Belgian Pilot have been made in Chapter 5.1</p>
<p>VERSION 3.0</p>	<p>July 2024</p>	<p>Amendments to the cover pages have been made. Conclusion sections for each pilot have been generated and these taken into consideration in the overall conclusions.</p>

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ACRONYMS

ADCP	Acoustic Doppler Current Profiler
D	Deliverables
DO	Dissolved Oxygen
OWF	Offshore Wind Farm
RIB	Rigid Inflatable Boat
ROV	Remote Operator Vehicle
TDS	Total Dissolved Oxygen
UAF	UNITED Assessment Framework
WP	Work Package



EXECUTIVE SUMMARY

This deliverable outlines the outcomes of the technical assessment and validation conducted within the UNITED project, focusing on the economic viability of pilot implementations. Guided by the UNITED assessment framework, the evaluation examines economic performance, ancillary environmental benefits, policy cohesion, uncertainty, robustness, and flexibility for each pilot and is based primarily upon the aggregated results from the Economic, Technical and Environmental pillar work packages, WP3, WP2, and WP4 respectively. Key aspects of economic evaluation encompass cost-effectiveness, safety enhancements, and environmental benefits, supported by outputs from these work package final deliverables. Where relevant, potential roadblocks resulting from policy, at either a regional or local scale and insights from other deliverables and workshops ensures policy coherence. These findings will support the creation of a Catalogue of Multi-Use blueprints (D1.5), aiding informed decision-making in the domain of multi-use offshore aquaculture systems.

1. INTRODUCTION

1.1. Scope and Objective of this deliverable

This report presents the findings of the technical assessment and validation conducted as part of the project, focusing on the economic acceptability of pilot implementations. The assessment considers the feasibility of an economic point of view, costs for other sectors, and the identification of possible trade-offs. The evaluation is carried out using the UNITED assessment framework, as defined in WP8, and has been implemented for each pilot. The primary objectives of this assessment include evaluating the economic performance of the solutions, estimating the ancillary environmental benefits, analysing distributional effects, addressing uncertainty, robustness, and flexibility, and ensuring policy consistency and coherence. These objectives are examined individually for each pilot, providing a comprehensive evaluation of the economic aspects and impact of the implemented solutions.

To assess the performance of the solutions, several sub-points have been defined. Firstly, the report examines the cost aspects, evaluating whether the new design is cheaper to build, maintain, deploy, and repair. Cost savings per unit of equipment, per euro earned, and per unit of production are considered. Additionally, the expected improvements in terms of safety and security, leading to avoided damages or loss, are assessed in WP3 and summarised here. Furthermore, the report investigates the environmental benefits associated with each solution, which connects to the findings of deliverables 8.3 and the report on WP4.

In order to ensure the economic acceptability of the pilot implementations, this deliverable relies on the outputs of deliverables 3.3 and 3.4. These outputs provide valuable insights into the economic viability and feasibility of the proposed solutions, allowing for a comprehensive assessment of their economic performance.

The estimation of ancillary environmental benefits is based on the outputs of deliverables 4.3 and 8.3. These deliverables provide the necessary information to evaluate the additional positive environmental impacts resulting from the implemented solutions.

In addition to the technical assessment, this report also incorporates the summarised outputs of deliverables 6.1 and 6.2, as well as the information collected from the WP6 workshop held in November 2022. This integration ensures policy consistency and coherence, enabling a thorough evaluation of the implemented solutions in alignment with established guidelines and regulations.

The outcomes of this deliverable, capturing the technical assessment and validation results, will contribute to deliverable 1.5, which entails the creation of a Catalogue of Multi-Use blueprints. The insights gained from this report will support the development of the catalogue by providing valuable information on the economic viability, environmental benefits, and policy implications of the implemented solutions.

1.2. UNITED Assessment Framework

The United Assessment Framework (UAF) is a generic iterative framework to assess impact of ocean multi-use projects. It can be adapted and applied to different a variety of applications, and the specific adaptations and

relevance to work packages and project structures and the five steps proposed in the framework are represented in Figure 1.

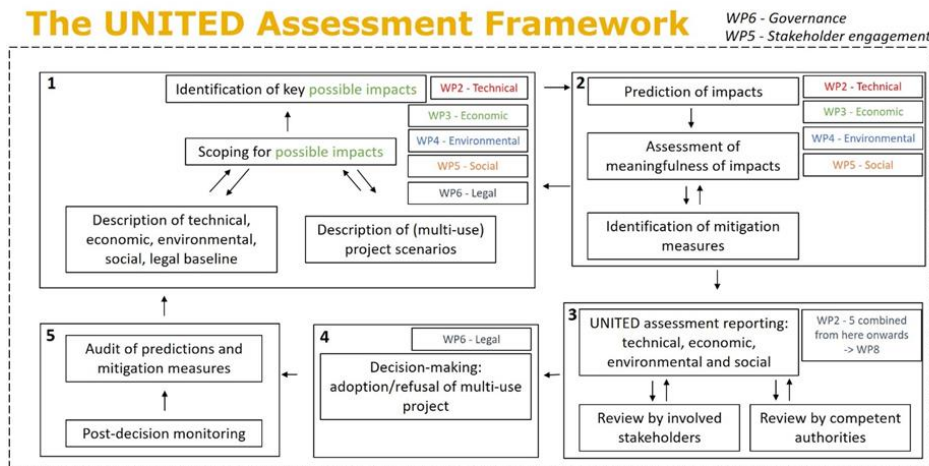


Figure 1 – The scheme of the UNITED Assessment Framework (UAF)

The first step of the assessment is to describe the baseline and the scenarios with which to work, then scope for impacts and identify the key impacts. The second step elaborates on the key impacts with prediction of their effect, assessment of their meaningfulness and identification of mitigation measures. The third step of the UAF is the reporting of the previously achieved assessment, accompanied by a review by relevant stakeholders and authorities. The fourth step is the decision making: adopt or refuse the project based on the impact assessment. The fifth and last step of the UAF post-decision monitoring and auditing of the predictions and mitigation measures.

The UAF can be generically applied and is used here to assess environmental, economic and social impacts, and also serves to evaluate the effectiveness of enabling pillars such as the legal and technical aspects. In the context of this report, the effectiveness of technical solutions for the pilots of UNITED is assessed. Within the UAF, deliverable 8.1, in parallel with deliverables 8.2 and 8.3, constitutes the third step of the framework: assessment reporting. The two first steps of the framework were addressed in WPs 2 to 6, with impacts and mitigation measures identified for each pillar of UNITED.

1.2.1. Comparisons

In order to determine the benefits and synergies which can result from the various technological and logistical configuration of the pilots, a comparison between singular use and combined used is required. This is done in a theoretical manner as outlined by the scenarios below. This comparison is key to highlight the plausible ramifications that new and emergent technologies tested within the UNITED project would have on economic and environmental factors. Additionally, the benefits and rationales for the selection of system or proposed benefits in the developed new system configurations are highlighted in the description of the pilot implementations and costs. These comparisons are executed in order to highlight seven key factors. Firstly, the costs, within the context of both operational costs and one-off costs, are considered. Reductions or increases are evaluated based on the system selected for implementation as well as the potential from synergies when combining multiple activities and benefits that could be realised in the co-development and operation of multi-use. Within the pilots such savings are not readily realised, as the pilots are often added to existing installations and have installed additional sensors and equipment in order to be able to operate semi-autonomously, however, where applicable, should the pilots be scaled to be truly multi-use and synergistic, additional saving and benefits are expected. These are highlighted both in the economic analysis of D 3.3 and annotated here. Furthermore the positive or negative environmental impacts are addressed, these are related to the selection of the design and the implication of implementation at scale.

Additionally, the capacity of the implemented solutions to avoid damages or losses is critical. Such avoided losses have resulted from a number of technical or technological undertakings including extensive historical and current monitoring, inclusion of trackers and recovery equipment on deployed structures and elements, system modelling, laboratory testing, and near-shore testing. This is particularly the case for the offshore mariculture system deployed within the North Sea in 3 of the 5 pilots, as the conditions which the multi-use systems endured are relatively severe when compared to near-shore and protected systems of similar design or nature. Such assurances for the avoidance of loss and damage are further required by legal and policy mandates, as these off-shore systems are not readily accessible and the loss or destruction of equipment due to failure or damage results in significant costs related to the recovery, removal, and replacement thereof. Such assurances are linked to the robustness of the system and design. The crossing point of sufficient robustness and financial burden to withstand the hostile and difficult marine conditions the pilots have been technically designed for while maintaining economically viable at scale is no small feat. The degree to which the robustness of the designs have withstood the demands of the deployment and operational regime are denoted alongside the uncertainties in the conditions to be weather and the growth and yield potentials of the systems.

Lastly, the cohesion of the policies and mandates which regulate and govern the design, deployment, and operation of the multi-use pilots has also been considered alongside the flexibility of these designs to be adapted and ported to other regions or sites. A combination of the policy regulations, and overall cohesion in National and European waters will determine the extent to which, given suitable flexibility of design specification to cope with a range of deployment conditions, the realised UNITED demonstrations can be ported and adopted to other locales.

1.2.2. Scenarios

Within the context of WP3, an economic analysis of the 5 different UNITED pilots are carried out according to a standardised cost benefit analysis, which looks into the fixed, one-off, and on-going costs that are realised by the singular and combined activities within each of the pilots. This is done for standardised theoretical scenarios fixing the size of development of the various demonstrator pilots and addressing the business cases potential for single use by each of the combined activities within this region, and then comparing the single use potential to the combined use. In this manner, using the economic assessment framework developed within WP3 and detailed in Deliverable 3.2, the potential impacts, either positive or negative are determined for the introduction of additional activities and the combination of efforts and scaling the demonstration activities implemented at the pilot sites. This theoretical scaling of activities is required in order to have a realistic assessment of the benefits, as the installation of trial equipment and demonstration activities will not result in a significant impact in terms of economic, environmental, or synergistic impacts within the demonstrators as implemented. As this was the standard assumption implemented within the Assessment of added value within WP3, we maintain the same assumption within the total assessment here.

1.2.3. Implementation of the framework in Pilots

Each of the five UNITED pilots are assessed on the seven key criteria detailed above: costs, avoided damages or losses, environmental effects, uncertainties, robustness, flexibility, and policy cohesion. The degree to which the monitoring schemes, technical designs, or implemented operations have impacted these criteria are evaluated on a per pilot level, utilising the relevant five project pillars. Using the UNITED assessment framework, primarily the economic and technological pillars, these criteria have been utilised in the identification and scoping of potential impacts, the prediction and assessment of the realised impacts, at the smaller demonstration scale realised within the project, and subsequently review and analysed within the context of scaling. This analysis resulting from the assessment framework's implementation, specifically on the technological components impact on costs and economic functioning of the pilots is summarised below.

2. TECHNICAL ASSESSMENT AND VALIDATION PER PILOT

In this section, the technical assessment and validation per pilot is done. For the assessment of the environmental benefits of the pilot implementations, further information can be found in D4.3 and D8.3 of the project. Deliverables 6.1 and 6.2 feed into the assessment of the policy information per pilot, as well as the WP6 workshop, which took place in November 2022 in Belgium. Further information on the costs per pilot can be found in WP3 and the summation of the comparisons completed in D 3.3 – Added value of Multi-Use incorporated as well.

2.1. German Pilot

2.1.1. Description of Implemented Design

The German Pilot is situated approximately 80 km west of the island Sylt, Germany in the North Sea. Despite the water depth being 22 meters, the area is characterized by significant wave heights up to 8m (max. 16m), strong winds, and swift currents (1.5m/sec). These conditions defines this location as an extreme offshore site in a highly energetic environment (ICES Working Group on Open Ocean Aquaculture).

Due to the considerable distance from the shore, the challenging nature of the surroundings and the proximity to three offshore wind farms, the system design must prioritize strength and durability. It is essential to create a design capable of withstanding the harsh forces of the environment without succumbing to damage. This approach aims to prevent any potential loss of the system, which encompasses environmental, financial, and safety considerations; predominantly those in relation to damage, loss of crops, and required salvage. Moreover, it also reduces the need for frequent boat trips for maintenance, thereby minimizing associated financial costs.

At the German Pilot a comprehensive aquaculture setup is implemented, encompassing a submerged mussel aquaculture system, a surface algae cultivation aquaculture system, and a sea bottom lander equipped with a fluoroprobe, an Acoustic Doppler Current Profiler (ADCP), and an echosounder among other standard sensors (see Figure 2). This instrument package collects valuable data about the underwater environment. The fluoroprobe measures chlorophyll fluorescence, providing insights into algae productivity and biomass. The ADCP allows for precise measurement of water currents, enabling the assessment of flow patterns and their impact on aquaculture systems. The echosounder detects and characterizes fish presence, assisting in understanding the interaction between aquaculture activities and the fish population. This integration of multiple components allows for comprehensive monitoring and measurement of mussel growth, algae productivity, and fish presence.

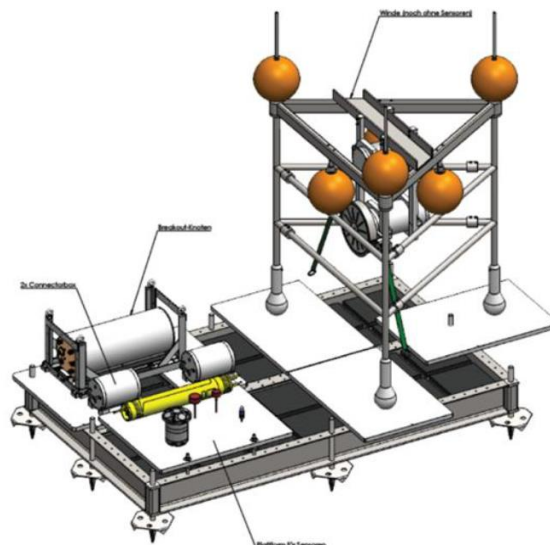


Figure 2 – Sea bottom lander at the German Pilot location

The submerged mussel aquaculture system (see top panel of Figure 3) utilised for cultivating mussels underwater, takes advantage of the nutrient-rich water in the North Sea and currents for high circulation. The mussels act as

natural filters, abstracting needed food stuffs and nutrients from the water column, affecting the water quality and contributing to the ecological balance of the marine ecosystem. This system not only provides a sustainable food source but also offers structural stability by forming mussel beds that attenuate wave energy. A backup monitoring system for the essential environmental parameters is attached directly to the mussel system to report on critical growth and health indicators.

The surface algae cultivation aquaculture system (see bottom panel of Figure 3) focused on cultivating algae at the water surface. Algae are known for their rapid growth and high nutrient uptake, which helps mitigate eutrophication through the removal of excess nutrients in water bodies and can therefore improve water quality. This system harnesses the photosynthetic capabilities of algae to enhance the overall health of the marine ecosystem.

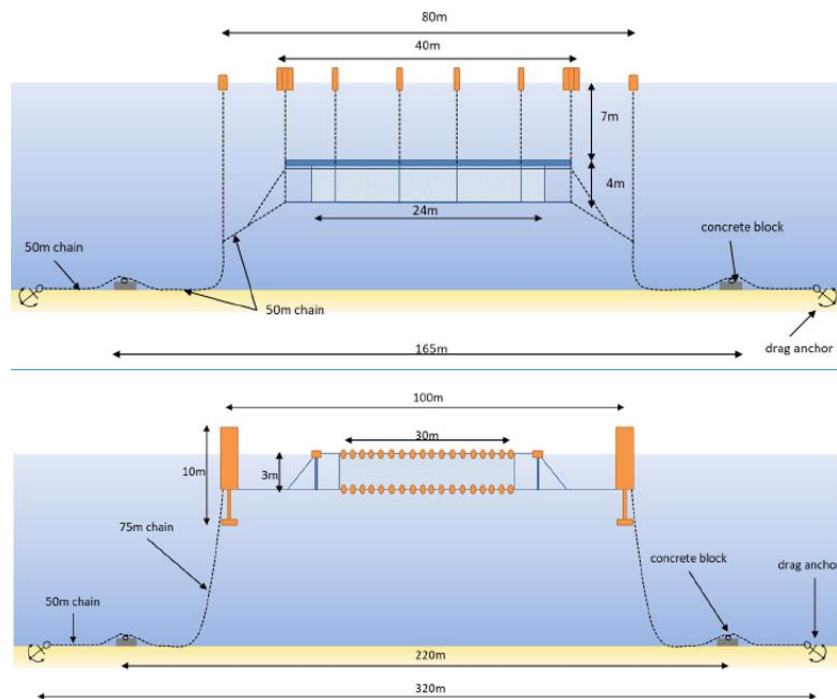


Figure 3 – Aquaculture systems; submerged system for mussels (top) and floating system for algae (below)

This integrated approach to aquaculture and monitoring ensures a comprehensive understanding of the ecosystem dynamics around the German Pilot station. By combining submerged mussel aquaculture with surface algae cultivation, and advanced monitoring technology, the project maximizes sustainability, promotes ecological balance, and contributes to local aquaculture and food production. The collected data from the sea bottom lander, the monitoring system on the mussel net and on the FINO3 platform (distance 300m) enables informed decision-making, optimizing aquaculture practices, and ensuring the preservation of the marine environment. Additionally, through the combination of the activities in one locale, the required information and monitoring systems can simultaneously serve both aquaculture activities as well as providing supplementary information to the wind farm operations, thereby increasing overall information gathering and knowledge at the site while spreading the costs of such information gather across multiple users.

2.1.2. Costs

A feasibility study for the German pilot (Geissler et al. 2018¹) has already considered the expected costs associated with multi-use offshore aquaculture systems for a commercial scale as a follow up scenario of the pilot. This study has thoroughly analysed and assessed the financial implications to ensure economic viability and long-term

¹ https://www.fh-kiel-gmbh.de/files/aktuelles/pdf/Machbarkeitsstudie_Offshore_Aquakultur_FuE-GmbH.pdf

sustainability of this pilot under various scenarios and implementing different types of aquaculture including macroalgae, mussels, oysters, rainbow trout, and an integrated multi-trophic aquaculture system. The expected costs encompass various aspects, including infrastructure development, equipment installation, operational expenses, maintenance, and monitoring. Factors such as materials, labour, energy, and technological requirements have been carefully evaluated to provide an accurate estimation of the financial investment necessary for the project. The feasibility study has also taken into account potential revenue streams, market demand, and profitability projections. By conducting a comprehensive economic analysis, the study has provided insights into the potential returns on investment and the commercial viability of multi-use offshore aquaculture systems. Specific per unit costing structure are reported in the Geissler report and are not recounted here, they have been adapted to a scaling study executed within the scope of UNITED reported below.

The UNITED economic scenario has been analysed in deliverables 1.3 and 3.3 of the UNITED project. Notably, when analyzing the numbers of the feasibility study, using the baseline assumptions, with a yearly harvest of 12,750 kg and an assumed market price per kg of 2 € from the assessment study, such a venture in the proposed configuration would not be profitable. A full analysis of the costing structures and breakdowns of the implemented configuration can be found within Deliverable 3.3, which denotes that operations at scale and an integration of the two sectors' operations could enable an offset of the projected venture loss. This is posed to be realized from a co-development and design, and mitigation of costs through shared use of vessels and resources; co-located but not integrated operations, as defined in the scaled scenario, would ultimately result in a loss using current market pricing and existing incentives (UNITED D3.3, 2023). According to the AG NASTAQ 2020 utilised in D3.3 in characterizing the costs and expansion potential of aquaculture in German waters, there are significant constraints to expanding mussel production beyond the already approved districts, and this necessitates any further growth in mussel aquaculture to be offshore, marking a pivotal shift in production dynamics. As offshore aquaculture in Germany is characterized by NASTAQ as still being in an experimental phase, with its development intricately bound to areas designated for Offshore Wind Farms (OWF) and the existing projects are primarily in the research phase, indicating that they do not yet hold any significant economic relevance, exacting costing and benefit structures for such activities at scale are theoretical. This underscores the nascent stage of offshore aquaculture in the region, highlighting the need for further research and development to ascertain its commercial viability through the work executed in UNITED and similar project.

Costing must therefore be considered within the bounds of these theoretical and projection exercises, with the reliability and sturdiness of design being a key element, coupled with ideal siting for maximized production potential. For offshore aquaculture to transition from an experimental activity to a commercially viable one, it is imperative that the concept is first successfully tested in pilots and demonstrator plants such as FINO3. This step is crucial as it lays the foundation for future expansion and commercialization, setting the stage for the industry to tap into its theoretical potential. As noted in the German case, cost savings are readily realized through the inclusion of multiple elements within one location as travel time and monitoring (remote and on-site) are high expenditures of the activities. Scaling is seen to reduce such costs as greater oversight can be undertaken at larger scales.

Additional elements which are not directly considered in the costing and operational planning of a scaled deployment are the environmental ramifications from consolidating economic activities in order to allow for additional environmental conservation and a potential overall increase in activities at sea. The benefits of multi-use in improving the environmental and social image of the offshore energy sector, stressing positive ecosystem services, co-use of increasingly limited sea space, and the pursuit of sustainable fishing and aquaculture is not quantifiable in this assessment, however can play a large role in public acceptance and the addition of incentives such as subsidies and the facilitation of permitting can aid in making these sectors economically viable (UNITED D3.1, 2022).

2.1.3. Avoided Damages or Loss

The effectiveness and reliability of the integrated system comprising the submerged aquaculture system, surface algae cultivation aquaculture system, and the sea bottom lander with monitoring instruments was validated through a rigorous process. Validation begins with the assessment of the design parameters and performance expectations of each component. Extensive simulations and modelling techniques from two external companies and the University of Ghent (algae system) were employed to replicate the environmental conditions and evaluate the system's response under various scenarios. These simulations help identify potential

vulnerabilities, assess the system's capability to withstand external forces, and optimize the design for maximum efficiency.

Physical testing is a crucial step in the validation process. Hence relevant parts of the system were deployed in the nearshore site in a calmer environment, mirroring the relevant physical and biological conditions. These tests measure and evaluate for example the accuracy of the monitoring instruments. By comparing the observed results with the expected outcomes, any necessary adjustments or modifications were made to ensure the system's performance aligned with the desired goals. Once the physical testing in the nearshore site was done, the system was validated through real-world deployments at the German Pilot site. Data was collected from the sea bottom lander, including fluorescence measurements and current profiles, which are cross-referenced with other relevant on-site observations directly on the aquaculture system and on the nearby offshore platform FINO3. These data points provide critical insights into the growth patterns of mussels and algae, as well as the presence and behaviour of fish and marine mammals in the ecosystem.

Continuous monitoring and data analysis are essential for ongoing validation and refinement. Regular inspections of the aquaculture systems were conducted by remote video and GPS trackers to assess their health, productivity, and structural integrity. The data collected by the sea bottom lander, the monitoring unit on the aquaculture system and on FINO3 was analysed, enabling the identification of trends, patterns, and potential anomalies. This information is crucial in refining the system design, optimizing the cultivation methods, and ensuring the accuracy and reliability of the monitoring instruments. Throughout the validation process, collaboration between scientists, engineers, licensing authorities and aquaculture experts were essential. The expertise of these multidisciplinary teams contributes to a holistic understanding of the system's performance and allowed for comprehensive validation.

By combining simulation, physical testing, real-world deployments, and continuous monitoring, the integrated system of submerged mussel-aquaculture, surface algae cultivation, and monitoring instruments was validated. This validation process ensured that the system met the required standards of performance, reliability, and sustainability. It provided the necessary confidence that the system will effectively contribute to the cultivation of mussels and algae, monitor their growth, and assess the presence and behaviour of flora and fauna including fish and highly protected marine mammals in the marine ecosystem.

2.1.4. Environmental Benefits

The environmental benefits of multi-use offshore aquaculture systems are also substantial. Assessment and validation of these benefits have been conducted across different aspects of marine ecosystems. Studies have confirmed that multi-use offshore aquaculture contributes to the conservation of marine biodiversity. The creation of artificial reefs and hard substrates, which have been removed during the last decades, by aquaculture structures has been assessed, confirming their role in enhancing fish populations and supporting overall biodiversity in the area (Stevenson et al., 2018). Furthermore, the presence of aquaculture structures attracting marine mammals and enriching the marine ecosystem has been observed at the German pilot site by the use of C-Pods and approx. 20 visual inspections and validated through scientific research (Thompson et al., 2019). An international certified external consulting office was commissioned to analyze and evaluate the C-Pod data.

Mussels and seaweed are low-trophic species. The cultivation of those species means no feeding, fertilizing or any external addition of substances and therefore excludes the additional input of nutrients to the environment, as opposed to higher trophic aquaculture such as fish. The enhanced water quality and nutrient cycling provided by large-scale multi-use offshore aquaculture in sheltered locations has already been reported, as these species can extract nutrients or organisms resulting therefrom, acting as a nutrient removal element as once harvested, they are extracted from the natural system (Lindahl et al 2005; Timmermann et. al. 2019; Xu et al 2023; Zollmann et al 2021). Mussels, that are farmed in these upscaled systems, effectively reduce waves and currents, benefiting other offshore activities by providing some protection for the structures, as suggested by Timmermann, and supporting aquaculture activities like seaweed farming. The nutrient concentrations released by molluscs have been measured, validating their role in stimulating seaweed growth and creating a positive feedback loop in the ecosystem. The water clearance ability of mussels, improving water clarity and increasing light penetration for seaweed growth in some locations, has also been assessed and confirmed and as cited in the above 4 studies, is expected to have significant positive impacts at scale within integrated farms and have auxiliary benefits for the

local and surrounding ecosystems when responsibly located to avoid overextraction, a factor of lower relevance in eutrophic waters. The compensatory effect of seaweed photosynthesis for the oxygen consumption of shellfish has been shown in studies, ensuring a balanced oxygen level in the water.

The assessment of space utilization and reduced environmental impact in multi-use offshore aquaculture is also promising. Measured in hard numbers, the overall space required for individual activities compared to the demonstrated increase in efficiency when combining different functions optimizes resource utilization, making more efficient use of marine areas. The utilization of freed space for other purposes, such as conservation efforts or sustainable tourism, has been shown to enhance the value and utilization of offshore areas. Additionally, studies have confirmed that integrating aquaculture within wind farms effectively protects the sea floor from invasive activities like bottom-trawling or sand extraction, preserving the integrity of marine ecosystems.

The shared vessel uses within these systems, resulting in fewer boat trips and reduced fuel consumption, has been measured and confirmed, leading to decreased carbon emissions. The presence of aquaculture structures providing additional biomass for fish and acting as shelter, nursery, and feeding areas has been shown to benefit fish populations and overall ecosystem health. Moreover, the organic enrichment of surrounding sediments due to organisms developing on wind turbines has been shown as a positive effect by supporting benthic communities and enhancing the local ecosystem.

Seaweed and shellfish, as low-trophic organism, are known to require no feeding, grow and reproduce quickly and abundantly, and provide a sustainable source of food or raw material for various industries. Also, the mitigation of eutrophication effects by seaweed and shellfish, through the removal of excessive organic matter from the water column, improving water quality and promoting ecosystem health has been approved by Ministers of Environment, Maritime Economy, Agriculture, and Fisheries of the Baltic Sea Member States and the Member of the European Commission in charge of 'Environment, Oceans and Fisheries' 2020: Declaration of the Ministers of Environment, Maritime Economy, Agriculture and Fisheries of Baltic Sea Member States and of the Commissioner for 'Environment, Oceans and Fisheries'.

In conclusion, the environmental benefits of multi-use offshore aquaculture systems have been shown in the Pilot and confirmed, assessed, and validated across various scientific publications. The conservation of biodiversity, enhanced fish populations, improved water quality, and reduced environmental impact have all been confirmed through scientific research and studies. These assessments provide robust evidence supporting the efficacy and sustainability of multi-use offshore aquaculture in addressing environmental challenges while meeting the growing demands for food, energy, and tourism in a responsible manner.

2.1.5. Uncertainty

Different areas of uncertainty can be discussed for the German multi-use pilot that are transferrable to all pilots:

The environmental impacts of these systems: Further study and evaluation are needed to understand and mitigate any unintended ecological consequences. This includes assessing the effects on water quality, ecosystem dynamics, and marine life. By further addressing these concerns, the long-term sustainability of multi-use offshore aquaculture can be ensured. While demonstrators and pilot activities as executed within the scope of this work can provide key information on growth rates, potential nutrient abstractions, and various other key data required for future projections, this data need to be utilised in modelling and scenario building in order to develop probabilistic impact mapping. Similar assessment have been previously carried out for the impact of fishing fleets on the benthic communities in the German EEZ such as those done by Stelzenmüller et al. 2014 and cumulative impacts from various marine spatial planning scenarios addressing combined or stacked pressures in marine zones by Furlan et al. 2020. When addressing the uncertainties of impacts and the potential reduction of impacts from usage consolidation, such multi-model and probabilistic approaches are required in order to best ascertain the intangible or indirect benefits of aggregating multiple activities.

The establishment of standardized regulatory frameworks. Clear guidelines and policies are necessary to address concerns such as site selection, permitting processes, and spatial planning. Developing a comprehensive regulatory framework will provide clarity and confidence to investors, operators, and stakeholders involved in multi-use offshore aquaculture.

Public acceptance and perception are critical factors that need to be addressed. Engaging with local communities, stakeholders, and the general public is essential to understand concerns, build trust, and foster understanding.

Open dialogue and effective communication will play a significant role in shaping the acceptance and successful implementation of multi-use offshore aquaculture systems.

2.1.6. Robustness

The German multi-use offshore aquaculture systems have demonstrated remarkable robustness in adverse weather conditions. The mussel system endured winter storms and rough seas throughout a full season in the open ocean, remaining intact. Similarly, the algae anchoring system withstood the same time in the open ocean, and the algae net yielded positive growth results after three months and marking the first successful offshore cultivation of algae in the German pilot. The resilience of these systems highlights their durability and adaptability, allowing them to navigate harsh marine environments effectively. Through appropriate design and engineering, multi-use offshore aquaculture systems can maintain their operations and achieve success even in challenging conditions.

The achievement of offshore-grown algae and mussels from the German pilot in May 2023 further validates the viability and resilience of these systems. The successful cultivation of these organisms in the open ocean demonstrates the potential for large-scale production and commercial viability.

2.1.7. Flexibility

Multi-use offshore aquaculture systems offer numerous environmental benefits and enhance the overall utilization of marine areas. The flexibility of these systems also allows for the efficient allocation of limited ocean space. By combining different functions, freed space can be utilized for conservation efforts, sustainable tourism, or other compatible activities. The modular nature of the system enables scalability and adaptability, allowing for incremental expansions and the integration of new technologies and practices. Adaptive management approaches ensure the continuous improvement of these systems, with data-driven decision-making and adjustments to optimize performance and minimize environmental impacts. The flexibility of multi-use offshore aquaculture systems provides a framework for sustainable development, balancing economic productivity with environmental stewardship in our oceans.

2.1.8. Policy Cohesion

Multi-use in wind farm zones may vary among EU member states, so the German (technical) solution needs thorough evaluation before being applied elsewhere. Federal plans for the Exclusive Economic Zone (EEZ) have been in place since 2009 for the North Sea and Baltic Sea. However, these plans do not currently address multi-use of the seas. Consequently, activities within offshore wind farms are neither prohibited nor approved, leading to uncertainty and placing much of the decision-making power regarding multi-use with the wind farm concession holder. Entry limitations imposed on offshore wind farms could impede multi-use in the German pilot. The fate of successful aquaculture farms once wind farms are decommissioned remains unclear. The new marine spatial plan may provide answers to these concerns. Until then, these unresolved issues pose financial feasibility challenges for projects within wind farms. All stakeholders in the pilots have obtained relevant insurances to cover all aspects. However, insuring loss of aquaculture products, such as mussels, at a reasonable cost is not feasible. Therefore, when conducting financial feasibility studies, the potential loss of mussels should be taken into consideration.

2.1.9. Conclusions

The aquaculture system developed and deployed was able to withstand considerable storm conditions in the exposed and harsh conditions offshore in the North Sea. This validates the robustness and integrity of the designed system and specifications used so that, if replicated at scale, this would prove a commercially viable schema to deploy and operate. This was also the case for the two systems operating in close proximity to one another, validating the potential for combinations thereof in a multi-use and co-location of these activities. Therefore, the testing and validation of the design in a real-world environment for prolonged periods has successfully raised the design TRL for the mussel and algae aquaculture system to the attended targets. From the costing and economic study undertaken, the design, given its potential to survive strong storms and maintain productivity for prolonged periods of time, represents a feasible deployment structure based on the desk study and theoretical bounds implemented. The environmental impacts realised from the scaled deployment are positive in so far as negligible effects were seen with some smaller positive impacts on local biodiversity and minimal changes to the

bio-physical conditions of the area. The potential implications of scaling and density configurations of deployment would need to be modelled and projected based on the results and nutrient uptakes realised in this demonstrator. Overall, the outcome of the German pilot was a success, with positive indications for scalability, robustness, and flexibility in the design to accommodate various avenues of scaling and replication.

2.2. Dutch Pilot

2.2.1. Description of Implemented Design

The Dutch pilot was installed at the “North Sea Farmers” Offshore Test Site, 12 km off the coast of The Hague and therefore subject to the rough exposed offshore conditions of the North Sea. At this location, two seaweed cultivation systems were installed by UNITED partner “The Seaweed Company” together with “North Sea Farmers” for two growing seasons. Next, a floating solar pilot (the first offshore floating solar installation in the world) was installed by UNITED partner “Oceans of Energy”. Additionally, a few measuring devices were installed. Both as part of the pilots (for example force measurement on the system) as well as with a big and a small data buoy by “North Sea Farmers”. All pilots were tested with the goal to install them as multi-use solutions in between the offshore wind farms. A full description of the systems can be found in D.7.1 (Review of pilot TRL, legal aspects, technical solutions and risks), D7.2 (Blueprint for the offshore site operation) and D7.4 (Joint production, monitoring, operation and maintenance protocol) for additional detailed information as the specifications and technical elements.



Figure 4 – Footage of Dutch pilot from left to right seaweed cultivation, floating solar and a small data buoy

2.2.2. Costs

As the Dutch pilot represented a demonstration pilot outside of a wind farm in order to demonstrate novel technical components which required sea trials and validation prior to being installed within an Offshore Wind Farm, the costs realised within this work are not directly comparable to operational challenges. Within the context of the economics work package, namely through United deliverables D3.1 and D3.3, as assessment of the market values and operational costs of such operations at scale have been performed, in a theoretical manner, with acknowledgement to the costs savings and potential benefits to be realised to directly couple such actions, which was not carried out within the project itself. For the assessment it is assumed that construction of the multi-use site occurs 2030, to align with the timeframe that UNITED industry pilot partner’s expect the offshore floating solar and seaweed industries could be delivered at commercial scale. This projection highlights that retrofitting PAWF to incorporate offshore solar and offshore seaweed cultivation is not considered a credible solution by pilot partners from an economics perspective. Costs are anticipated to be too high for low potential production levels given the existing wind farms and capacity to include these activities via retrofitting. As a result, it is assumed that the PAWF offshore wind infrastructure would be installed at the same time as the other multi-use infrastructure in a complete renewal of the site’s infrastructure, rather than a retrofit, and have a pre-requisite of a co-development and co-design aspect in order to be able to achieve profitability and commercial viability.

Golroodbari et al. (2021) assessed the feasibility of adding an offshore floating solar farm to the already existing OWF Borssele I & II. From this paper it can be concluded that Offshore Floating PhotoVoltaic (OFPV) solar is currently not yet commercially viable. To make OFPV commercially viable, the marginal solar power delivered to the grid should be improved and the costs for OFPV should be reduced. This implies that subsidies from GoN are essential to support the further development of this sector (Golroodbari et al., 2021). Economies of scale are of crucial importance to the commercial viability of OFPV. According to industry experts, the scale is relevant for

projects up to approximately 30 MWp; after this point economies of scale are a less important influence on commercial viability (World Bank, 2019).

A 25-year operating lifespan for the offshore solar before decommissioning is assumed; an operating lifespan of 25 years is assumed for the seaweed. A practical assumption bases the site layout would be 1/3 dedicated to wind power, 1/3 solar, 1/3 seaweed is made with the exact layout of a multi-use at sea site would be subject to detailed engineering design and feasibility work and planning permissions from the Dutch Government. Given these criteria, it is envisioned that using the techniques (Deliverable 7.1) and combinations potential which has been realised through the offshore pilot testing, approximately 460 ha or 3,300 tonnes per year of production of seaweed in the site is possible. This is approximately 1/3 of NSF projections for greater North Sea seaweed production by 2035 (Zinzi to insert source). This would require 150 systems and 300 anchors to deliver. Pilot partners Oceans of Energy consider that approximately 120 MW capacity of energy production for offshore floating solar is possible given 120 MW of offshore wind capacity and the corresponding grid export cable capacity. Additional costing structures, required subsidies, and potential economic benefits from this integration is discussed in depth within UNITED D3.3.

Reduction in costs for combined efforts have similar aspects as those discussed within the German pilot. With the presence of multiple actors within a certain region, cross-trained personnel would be able to make early detections in the deterioration of equipment at sea, thereby allowing for earlier detection of faults or potential failures, resulting in a higher potential to enact maintenance procedures and replacements prior to failure, potentially lowering insurance costs, salvage operations, and lost production. Additionally, some maintenance and operational activities were possible to be jointly carried out on the same sea-going missions, a significant cost for smaller projects and pilots, which benefited the co-location of these activities. While when operating at scale, the frequency of required visits is expected to increase due to the increase in the number of activities and time to be spend at site, operations which are possible from the same or specialised multi-use vessels would further reduce these costs and allow for a streamlining of the efficiency of each voyage. Furthermore, as within the German pilot, OFPV and seaweed aquaculture benefited from mutual monitoring equipment. With additional activities located within a small area, the benefit from each piece of monitoring equipment is shared amongst the actors operating within the vicinity, this also increases the potential number of monitoring points and breadth of data to be collected, both remotely and in-situ.

Challenges with increased prices of materials, fuel and equipment have been overcome within the pilot, however, given then continued increase in raw materials and fluctuating markets, there is noted volatility in the exact pricing and estimation of costs and benefits when combining activities and the requirement for additional infrastructure to support increased activities (though it is expected to be a lower cost that implementing the same activities as individual use). In the Netherlands, both for seaweed cultivation (in 2023) and for floating solar (in 2025) the next steps are made to install the systems within a wind farm. The first years are expected to be an innovation phase, which will be followed by the commercial phase. With support of subsidy innovation projects, investors and subsidy programs for the gap between the costs and revenues in the beginning of the development, it is expected that both multi-use sectors will become commercially interesting.

2.2.3. Avoided Damages or Loss

The North Sea is one of the most challenging offshore environments for offshore installations. Therefore, it is important to think carefully about a convenient approach in advance. For the Dutch pilot this was done in three stages: 1) in the design; 2) in remote monitoring; 3) in the operation & maintenance.

For the design it was important to use element in the installation that can handle the rough North Sea conditions. In addition, the installations of the seaweed cultivation system and the floating solar were designed in such a way that there is no single point of failure.

During the operational phase, both the environmental conditions (wave, wind, etc.) were closely monitored as well as the installations themselves. Think of GPS, load sensors and cameras. In case there would be an incident where for example part the structure would come loose, this could be measured by a shift in the GPS coordinates, a drop in the load measured by the load sensor or visually on the camera. By doing this, it was immediately known via this remote monitoring data on an online dashboard when something was not right. This allowed immediate action to be taken when necessary and avoid further damages or loss. Finally, during the operational phase regularly inspections took place to check the installations to avoid damages or loss in an early stage. Next, after severe storms, additional inspection trips were made.

By using this approach, the installations survive several storms: “Ciara”, “Dennis” and “Bella” in 2020 with wind speeds up to 62 knots and waves up to 9-10 m; “Evert” in 2021 and “Corrie”, “Dudley”, “Eunice” and “Franklin” in 2022 with Eunice being in the top 5 heaviest storms of the past 52 years.



Figure 5 – View of the sea from our on board camera at the floating solar installation by “Oceans of Energy” 1/2/2022

2.2.4. Environmental Benefits

The environmental impact is also discussed in the deliverables D4.3 & D8.3. For the Dutch pilot, with floating solar and seaweed cultivation; there are several key environmental benefits that have been identified through this work. Addressing environmental benefits at sea, seaweed cultivation can potentially improve the biodiversity and water quality, similar as to the benefits realised in the German pilot in this regard. As both pilots are located within the North Sea and have looked at the forward prognosis of expanding to similar areas, the potential benefit from nutrient sequestration, increase in water clarity, reduction in algal blooms, etc. are similar across both of the pilots. In addition, for both forms of multi-use holds that by combining activities (“multi-use”), there is more space left for nature or other activities. This, as in with the German pilot, allows for an increased in the amount of marine space that can be delineated for nature, protected through the enacting of Marine Protected Areas (MPAs) or MPA Corridors, while accommodating the foreseen and planned expansion of marine activities. Next, the Dutch Pilot Partners denote that their anchors of the multi-use installations can create habitats for certain species. When designed and installed with Nature Inclusive Design (NID) parameters and considerations, such installations can recreate lost habitats and be strategically located in order to promote the restoration of degraded or destroyed habitats. To what extent these benefits occur needs to be further investigated. Therefore, large-scale pilots that are monitored for a longer period of time are required, as well as determining the impacts and lost benefits from the removal of such structure after the service life of projects and activities.

These offshore multi-use activities in addition both need, as is in the name, no space on land. In addition, for the cultivation of seaweed no fresh water is needed. When seaweed is used to replace “dirty” (raw) materials, for example plastics, the value chain of product can become cleaner. Looking at floating solar, it can produce of course cleaner energy than fossil fuels. Next to no need for land, by combining offshore floating solar with the wind farm energy network, the energy cable can be used more efficient. This result is a more constant energy supply.

2.2.5. Uncertainty

As mentioned for the German pilot, these uncertainties can be discussed for the Dutch pilot as well. And of course, offshore operations in general come with uncertainties on the operation as it is quite weather dependent. This holds for all the pilots as well. Pilots like the ones in UNITED help to tackle these uncertainties together and learn from one another.

2.2.6. Robustness

The Dutch pilot installations with seaweed cultivation and floating solar have demonstrated a great robustness in the rough weather conditions of the North Sea. The installations have survived the storms mentioned in paragraph 2.2.3, with a huge achievement. This offers great prospects for both sectors: successful offshore seaweed cultivation and floating solar panels.

The robustness of the installations during the whole lifetime (~25 years) needs to be further studied during the coming years with long-term pilots. With these studies, for example the effect of corrosion on the strength of the systems can be investigated.

2.2.7. Flexibility

The flexibility of the multi-use activities in the Dutch pilot can be discussed in different ways.

First of all, the structures themselves: both the seaweed cultivation installation as well as the floating solar installation need to be flexible to resist the rough offshore conditions. Especially the currents and high waves. The seaweed installation is completely flexible with flexible anchor chains, flexible floaters and a flexible net structure. The whole installation can move in the water with the waves and currents. The floating solar installation consists of flexible anchor chains and rigid floaters with solar panels. These floaters are connected to each other in a flexible way. Thereby the whole installation can move along with the waves.

Next, within the operation flexibility is necessary as well. Due to the offshore location, the work needs to be planned when the weather conditions are acceptable to go offshore. Therefore, the staff and organisation need to be flexible to adjust the activities based on the weather when needed.

Last, it is interesting to mention that the market for seaweed cultivation is flexible as well. When seaweed is produced, there are several markets that can buy the seaweed for their products. Amongst others: food, feed, bio-stimulants and biomaterials. When one market is not going well, the seaweed farmer can sell his seaweed to another market. This makes the seaweed industry flexible at the market side as well.

2.2.8. Policy Cohesion

The Dutch pilot is located at the “North Sea Farmers” Offshore Test Site. For this location, the “North Sea Farmers” have a permit for testing innovations in the field of seaweed cultivation and other forms of multi-use. Therefore, there was no need for an additional permit for the activities within the Dutch pilot. They took place within the current permit of “North Sea Farmers”.

For the offshore wind farms (OWF) in the Netherlands, the current policy is that every new OWF needs to open up for multi-use. The “old” first windfarms are closed for other activities, but with Borssele as a start and followed by Hollandse Kust Zuid in October 2023, in every new windfarm multi-use will be possible. The construction phase of a OWF first needs to be finished. Then the operational phase starts. At that moment, the OWF “opens up” for multi-use, including an area passport. This area passport is a map of the OWF with indicated at which location, what type of multi-use can take place. This approach is part of the North Sea Agreement.

Together with all the partners involved in the North Sea Agreement and new users, like for example the seaweed industry and floating solar parties, there is a North Sea Consultation every month to discuss the implementation of the North Sea Agreement. Within connected working group “multi-use” this policy is discussed as well. In addition, one of the latest tenders for a new OWF included floating solar as part of the tender criteria. There are two OWF coming up including one with an installation of Oceans of Energy. For the seaweed cultivation, a permit application for the first farm is submitted for installation Q3-Q4 2023.

Deliverables D6.1 and D6.2 include additional elements on the policy cohesion in the Netherlands.

2.2.9. Conclusions

The seaweed aquaculture system, floating solar configurations, and data buoys deployed and tested in the North Sea Farm testing fields resulted in a successful deployment of the three elements under similar conditions and in the same area, though not in an integrated multi-use approach. This validates the robustness and integrity of the designed system and specifications used so that, if replicated at scale, this would prove a commercially viable schema to deploy and operate. The coming phase would result in the integration of these various elements in a combined configuration to validate and realise the TRL and validation of combining the elements into a true multi-

use project, however, the validation of singular elements under the same conditions is the first step in paving the way to integration. As noted in the avoided damage and losses, these structures withstood formidable storms, outside of the normal operational parameters, thereby underpinning their robustness. The cost and economic analysis conducted indicates that the design of the floating solar array, seaweed aquaculture, and data buoy deployment is highly feasible. The structure's robustness allows it to withstand strong storms while maintaining productivity over extended periods. This feasibility is supported by desk studies and theoretical models. Environmental impacts from the scaled deployment are generally positive, showing negligible negative effects and some minor improvements in local biodiversity with changes to the biophysical conditions of the area noted to be minimal, though this is highly influenced by the small scale of deployment. However, to fully understand the implications of scaling and density configurations, further modelling and projections are necessary; these should be based on initial monitoring results and consider different combinations and densities of the structures to optimize environmental and economic outcomes, though the market potential for the seaweed cultivation and additional green energy produced by the two core demonstration activities is flexible and positive to further developments, thereby making future scaled deployments likely and beneficial from a social and economic perspective while being technically sound and viable.

2.3. Belgian Pilot

2.3.1. Description of Implemented Design

The Belgian pilot is situated at two test locations in the Southern North Sea. The nearshore test site 5 km off the coast at Nieuwpoort (Westdiep) facilitated optimizing cultivation techniques of the European flat oyster (*Ostrea edulis*) and sugar kelp (*Saccharina latissima*) as well as improving restoration procedures. The best performing methods were then implemented at the offshore test site within the operating wind farm Belwind (operated by Parkwind), 46 km off the Belgian coastline (Figure 6), with a total capacity of 165 MW, powering up to 175 000 households.

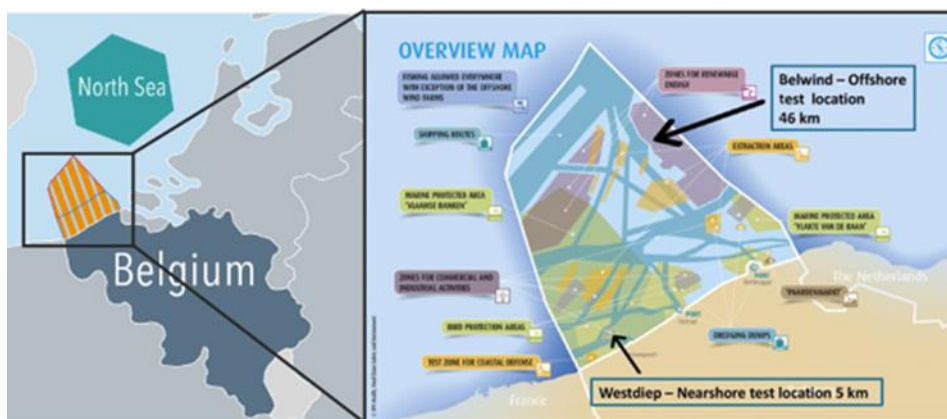


Figure 6 – Belgian pilot test locations of the Westdiep (nearshore test site) and Belwind (offshore test site) and marine spatial plan of the Belgian part of the North Sea

The Belwind offshore wind farm is located at the Bligh Bank and its surrounding gullies where the sea depth varies between 15 and 37 meters. The area is characterized by sandbanks and gullies that are formed and sustained by the tidal currents. The pilot multi-use combines seaweed and European flat oyster (*Ostrea edulis*) aquaculture, and oyster reef restoration within an offshore wind farm.

The Belgian pilot's challenges for design and construction have been mainly related to: 1) its relatively long distance (46 km) from the coast; 2) rough conditions with 6 m waves not being an exception; 3) its location in a wind farm, posing requirements on risk assessments.

To make sure the installations envisaged would comply with and resist to the challenging nature in these offshore circumstances, engineering teams have modelled the structures which were implemented. Moreover, installation methods which respect to the maximum the environment and sustainability were kept in mind.

In 2022, two separate longline systems were installed in the offshore Belwind site: one system for oyster cultivation and the other for seaweed cultivation. Several different types of cultivation structures were dispersed along the oyster backbone to determine best practices for oyster grow out offshore. The seaweed longline used a net system for grow out and tested two different methods of seeding.

The Belgian pilot also conducted a feasibility study for oyster restoration by installing four restoration tables on the sea floor in the Belwind concession area. These four restoration tables were installed on the existing scour protection around two monopiles. Tables were placed on the sea floor at a safe distance from the wind turbines. Moreover, the non-exclusion site around the monopile (= e.g. landing and cable site) was avoided.



Figure 7 – Restoration tables begin installed near the wind farm site

Per monopile, two tables were installed: 1 structure in SW-NE axis and one on SE-NW axis, to estimate whether the place around the monopile could influence the settlement of oysters. Per table, 6 smaller compartment called “gabions” were filled with scour protection materials.

More details on the structures and design implemented can be found in D7.7.

2.3.2. Costs

A feasibility study for the Belgian pilot was set-up during the UNITED project to analyse and assess the financial implications to ensure economic viability and long-term sustainability. Just as for the German pilot, the expected costs encompassed various aspects, including infrastructure development, equipment installation, operational expenses, maintenance, and monitoring. Factors such as materials, labour, energy, and technological requirements have been carefully evaluated to provide an accurate estimation of the financial investment necessary for the project.

The feasibility study has also taken into account potential revenue streams, market demand, and profitability projections. By conducting a comprehensive economic analysis, the study is to provide insights into the potential returns on investment and the commercial viability of multi-use offshore aquaculture systems. More details can be found in the Belgian business case deliverables.

2.3.3. Avoided Damages or Loss

The effectiveness and reliability of the integrated system comprised the submerged aquaculture longlines and the sea bottom oyster cages.

To avoid damages within the windfarm, we set up the following contingency plan :

The following measures are taken in order to reduce the risks to a maximum :

- The installation of the screw anchors and the submerged longlines for oyster and seaweed cultivation was done by an experienced companies.
 - In order to reduce the impact of the waves and hence stimulate the biological growth while minimizing risks of loss, the backbones offshore were installed below the sea surface as described in UNITED's deliverable D7.2.
 - In the design of the final backbones, both for seaweed and oyster, the largest waves and strongest currents occurring in a 50-year period have been used to calculate the necessary dimensions of anchors, mooring ropes and backbones, while in addition, a safety factor of 3.45 has been applied (D7.2)
 - One of the major concerns during the installation, is to keep the vessel fixed at the location while drilling to install anchors or while installing the backbone or sampling. Therefore, vessels using working class ROV, 4-point anchoring or DP2 have been applied for installation and sampling of the structures in the offshore wind farms. Partner JDN carried out an extensive market study to identify the most suitable partner, together with Parkwind and UGent.
- Every activity that took place in the windfarm, was described into detail in the method statement (drafted per mission, adjusted to the vessel which was chartered) and approved by the concession holder.
- Modelling of the longline design by UGent Maritime Technology Division.
- Modelling of the oyster restoration structures by JDN engineering team
- In the pre-operational phase, tests with the experiment longlines and were carried out nearshore to better understand the behavior of the system.
- Experimental set-up has been installed at the edge of the parc (away from cables) to minimize risks of damage in case a longline would break free
- It was opted to install the two lines far away from each other, so in case 1 line breaks the other line would not be compromised. Also, it gave more freedom for vessels to manoeuvre when samples were to be taken in course of the project.
- The risks involved with the installation and decommissioning of the experimental longlines and bottom culture infrastructures as well as with the sampling campaigns were evaluated by an external consultant Mott MacDonald. Their technical report was submitted to the board of Parkwind to give permission to deploy the planned activities.
- All the partners had already experience with experimental set-ups for aquaculture offshore (cf. Edulis project)
- Pingers were attached to the aquaculture systems, to retrieve more easily the items in case they detached from the backbone.
- Frequent monitoring was performed, e.g. via the crew and research vessels that passed through the area on their own missions.

2.3.4. Environmental Benefits

- Anchor system : the Belgian pilot decided to opt for screw anchors to anchor the backbone offshore, to have as less as possible disturbance of the bottom compared to other types of anchors dredging over the bottom.
- The location where the backbones and the restoration tables have been installed, takes into account the biological requirements of flat oysters and seaweed but are chosen and approved by the HSSE of Belwind, such that the consequences of a loose backbone or problematic deployment of the tables are minimized (at the outskirts of the wind farm, away from cables).
- In order to reduce corrosion due to electrolysis of the galvanized stainless-steel restoration tables (and risk of loss of materials due to breaking of the structures), sacrificial anodes in zinc have been attached to the

tables. This has been tested via the nearshore tables that had been over one year in the seawater before installing the structures offshore, and only showed minor signs of corrosion.

- As the windfarms' vessels and research vessels that passed by in the area also helped in monitoring the surface buoys, this allowed for frequent updates on the system's functioning while minimizing the vessels that needed to be chartered, hence resulting in fewer boat trips and reduced fuel consumption. The latter is important to decrease carbon emissions.
- The presence of the restoration (and aquaculture) structures providing additional biomass for fish and acting as shelter, nursery, and feeding areas has been shown to benefit fish populations and overall ecosystem health. Moreover, the organic enrichment of surrounding sediments due to organisms developing on wind turbines has been shown as a positive effect by supporting benthic communities and enhancing the local ecosystem.
- As only extractive species have been integrated with wind energy in the Belgian pilot, this multi-use cultivation could potentially improve the biodiversity and water quality.

More details on the environmental impact are being discussed in the UNITED deliverables D4.3 & D8.3. Main conclusion here which apply for the Belgian pilot are, that ocean multi-use holds a strong potential as a tool for achieving European environmental goals and strategies. The strongest potential synergies from an environmental perspective have been attributed to the combination of low-trophic aquaculture and offshore windfarms. This combination provides many benefits for the marine ecosystem, including:

- an enhanced increase in biodiversity thanks to the artificial reef effect;
- a stronger protection of the seafloor thanks to an absolute incompatibility with bottom trawling;
- the potential for implementing restoration measures such as flat oyster reefs restoration in the Belgian part of the North Sea and even beyond;
- an increased carbon sink thanks to more organic matter ending increasing sedimentation on the seafloor;
- a potential for mitigation of eutrophication effects thanks to an increase in suspension feeding organisms (oysters);
- a potential for spill-over effect from the shelter and nursery offered by the multi-use area;
- a reduction of overall underwater noise and carbon footprint due to combined boat uses;
- Wind farms and low-trophic aquaculture being space-demanding activities, combining them would reduce conflicts with other sectors and increase their acceptability from the general public and from other users of marine space and resources. The last point is essential, when taking into considerations European plans of increasing renewable energy production and sustainable, local food production, as foreseen in the Green Deal.
- If implemented and managed correctly, the multi-use as implemented in the Belgian pilot can, from an environmental perspective, present interesting potential positive synergies

Because of all these potential positive environmental synergies, the combination of offshore wind farms and low trophic aquaculture might fit in the OECM category, support conservation efforts and help State Members to achieve the 2030 Biodiversity goals. It must also be noted that the Belgian pilot is only at experimental stages and therefore required to design up-scaled scenarios on which environmental impacts could be predicted. These up-scaled scenarios are used across all work packages of UNITED, to ensure homogeneity. For more information about the scenarios used to conduct the environmental impact analysis, please refer to Annex 2 of the UNITED deliverable 4.3.

2.3.5. Uncertainty

In the pursuit of our multi-use offshore aquaculture project in Belgium, we have been acutely aware of the uncertainties that could impact our progress and outcomes. Similar to our German counterparts, the environmental implications of our efforts require further study. As the Belgian pilot is still in its experimental stages, we have undertaken the task of designing upscaled scenarios. These scenarios will enable us to better predict the environmental effects of our activities. Understanding these impacts is not only pivotal for sound environmental management but is also crucial in addressing any concerns that may arise within the community. This proactive approach serves to foster public acceptance of our offshore work, engendering trust and goodwill in our conservation efforts.

In the realm of economic feasibility, attracting investors is essential to the success of our project. Therefore, it is imperative that we present a realistic and compelling business case. Our multi-use offshore aquaculture project is intricate, requiring substantial financial support. Upscaled scenarios allow us to demonstrate the economic viability of our endeavour, making it an attractive proposition for potential investors.

Regulatory frameworks play a pivotal role in ensuring the responsible development of our project. These frameworks must provide clear guidance on site selection, permitting processes, and spatial planning. A comprehensive regulatory framework not only ensures legal compliance but also imparts confidence to investors, operators, and stakeholders. It forms the cornerstone of responsible and efficient project management.

The unpredictable nature of the weather is a constant factor that governs our activities at sea. Safety remains paramount, and adherence to rigorous safety protocols, coupled with real-time weather monitoring, is crucial to safeguard the well-being of our personnel and the integrity of the project.

In our project, unexpected costs and material retrieval are significant considerations. Loss of materials within the wind farm area necessitates the chartering of vessels for retrieval, a contractual obligation with the wind farm. It is our commitment to ensure that every element installed in the wind farm area is retrieved and decommissioned at the conclusion of the project, exemplifying our dedication to environmental responsibility.

Finally, the emergence of unforeseen global events, such as the COVID-19 pandemic, has highlighted the importance of adaptability. The pandemic resulted in unexpected delays. Moreover, the energy crisis and inflation impacted the costs of both labour and materials. To ensure project resilience, we have learned to adapt to these unforeseen challenges, demonstrating our commitment to the success and sustainability of our multi-use offshore aquaculture project.

2.3.6. Robustness

Our venture into Belgian nearshore aquaculture systems was marked by a dynamic process of refinement and adaptability. Through intermediary samplings and hands-on experience, we made significant adjustments to our designs, ultimately ensuring the success of our offshore trials.

- **Basket systems transformation:** During the intermediary samplings in nearshore conditions, it became evident that certain basket systems were ineffective. Notably, open frame systems, to which we initially attached the baskets, proved vulnerable as baskets were lost. In response, we decided to abandon these systems for our offshore trials. A more successful approach involved the design of closed cages, in which oyster baskets could be securely placed. This transformation allowed us to maintain control and functionality, even in offshore environments.
- **Seaweed net enhancements:** Our journey with seaweed nets led us to a crucial realization. Lighter nets exhibited a tendency to tear apart at the connections with the backbone, prompting their abandonment for offshore trials. To address this, we fortified the connections to the backbone, ensuring the longevity and stability of the nets in the demanding offshore setting.
- **Robustness and oyster attachment:** We encountered varied results in terms of robustness. While some systems, such as the bamboo sticks in the racks, displayed remarkable resilience, oysters cemented or glued to these sticks were vulnerable to the strong offshore currents. Consequently, bamboo sticks were phased out for offshore trials. In contrast, oysters cemented to ropes demonstrated resilience, although they attracted significant fouling. Anticipating reduced fouling offshore, we opted to retain the design of oysters cemented to ropes for our offshore operations.

- Challenges faced: Despite our diligent precautions and the adjustments made to our offshore longlines, we did experience some setbacks. Following a severe storm, we lost a cage at sea. However, the cage was equipped with a pinger, enabling us to track and recover it. Similarly, a seaweed net with metal chains at its lower end became lost at sea but could be located through scanning the seabed.
- Resilience of restoration cages: It is worth noting that the robustness of our restoration cages remained consistent in both nearshore and offshore designs, validating their efficacy and stability throughout the duration of the pilot.

2.3.7. Flexibility

In the endeavour to combine oyster and seaweed aquaculture with oyster restoration within an offshore wind farm, flexibility has been a cornerstone of our approach. This flexibility extends to various aspects of our project, enabling us to adapt to the dynamic challenges of offshore operations and maximize the potential for success.

- Flexibility in aquaculture structures: Prior to deploying our aquaculture structures offshore, extensive planning and calculations were undertaken. The careful consideration of buoyancy, in combination with the expertise of our crew, ensured that the aquaculture longlines remained inherently flexible within the water environment. By optimizing buoyancy, our structures were designed to seamlessly adjust to the natural motion of the water and gracefully glide through waves, rather than engaging in a continuous battle against the forces at play. This flexibility not only enhances the stability of our aquaculture operations but also minimizes the risk of damage in challenging offshore conditions.
- Flexibility in crew operations: Adverse weather conditions can significantly impact offshore activities. In recognition of this, our pilot placed a strong emphasis on the flexibility of our crew. When favorable weather conditions permitted, the project team had to be ready to mobilize swiftly, transitioning from onshore to offshore operations. Effective communication and coordination were key in this process. A dedicated approach to readiness and preparedness ensured that when the captain signaled the green light, the crew could promptly move offshore for sampling and other necessary tasks. This adaptability was essential for maximizing the productivity and efficiency of the pilot's operations, ensuring that opportunities were done in a timely manner.
- Adaptive resource allocation: In our project, flexibility extended to how we managed our resources. The marine environment is constantly changing, with varying conditions and challenges. To address these changes effectively, we had to adjust how we allocated our personnel, equipment, and materials. This means that we allocated our resources to the areas of the project that needed them the most at any given time. For example, if a particular aspect of the project required more hands-on deck or specialized equipment due to unforeseen challenges, we could quickly shift our resources to meet those needs. This adaptive resource allocation allowed us to respond effectively to unexpected issues and ensure that our project remained efficient and successful.
- Environmental monitoring and weather considerations: The offshore environment was subject to a range of ecological conditions and weather fluctuations. In response to this variability, our project demonstrated flexibility by closely monitoring environmental parameters, ensuring that aquaculture crops were installed at the most opportune times. This proactive approach allowed us to harmonize our aquaculture and restoration activities with the local conditions. For example, we continually monitored weather conditions, such as wind patterns, sea currents, and temperature variations. This thorough environmental monitoring allowed us to make informed decisions about when to install the aquaculture structures. We aimed to choose optimal times when weather conditions were favorable, ensuring the safety of our operations and the well-being of the aquaculture crops.

In summary, our multi-use offshore Belgian pilot stands as a testament to the power of flexibility in successfully combining oyster and seaweed aquaculture with oyster restoration within an offshore wind farm. Flexibility is ingrained in our approach to aquaculture structures, crew operations, resource allocation, and our commitment to environmental responsibility. Only by being adaptable and responsive to the ever-changing conditions of the marine environment, we ensure the resilience and overall success of our ambitious undertaking.

2.3.8. Policy Cohesion

In crafting a policy framework for multi-use offshore projects in Belgium, several key factors should be taken into account. First, the unique marine ecosystem of Belgium necessitates a dedicated assessment of environmental impacts and adaptations tailored to its specific characteristics. This entails the formulation of regulations within our Marine Spatial Plan that address the distinct nature of Belgian waters and marine life. Second, community engagement plays a pivotal role in gaining acceptance and support for multi-use offshore projects. Policies should prioritize active engagement and collaboration with local stakeholders, fostering trust and effectively addressing their concerns. Third, while economic feasibility is a universal concern, Belgium's financial landscape and investment opportunities may differ from other countries. Therefore, policies should support the creation of a compelling business case that is tailored to the Belgian market. Fourth, Belgium's climate and weather conditions require policies that prioritize safety at sea and incorporate adaptability to varying weather patterns, ensuring the well-being of personnel and the integrity of the project. Finally, recent global crises, such as the COVID-19 pandemic and energy challenges, have underscored the importance of policy flexibility and adaptability. Belgium should be well-prepared to navigate unforeseen challenges effectively and respond with resilience.

UNITED deliverables D6.1 and D6.2 include specific elements on the policy cohesion in Belgium.

2.3.9. Conclusions

Similarly to the German and Dutch pilots investigations into low-trophic aquaculture, the Belgian deployment of oyster and seaweed systems within the North Sea provided to be a success, with the system operating according to design and producing positive yields of both oysters and seaweed. New insights were gained on the susceptibility of the anchoring systems to potential degradation from larger storm events, particularly in quick succession, and this information has been taken into consideration for further refinement of designs for future deployment and scaling. Additionally the materials and strengths of the net systems have been enhanced through the modeling efforts undertaken in the UNITED project as well as the results from the field deployment of these structures. These enhancements in design are critical for raising the TRL level of the solutions trialed, and the resulting need for refinement exhibits the importance of real-life condition testing and deployment prior to scaled production and roll-out. The benefits and impacts in the local bio-physical area reflect similar findings as those in the German and Dutch Cases. The unique element of oyster reef restoration and nature inclusive design elements implemented in this case has resulted in positive results for the design and scalability of these solutions and the benefits to the bio-physical systems in which they are located. The integration of all of these elements in a collaborative and co-located system demonstrates the ability for the various solutions to be implemented in one location as components to a multi-use solution.

2.4. Danish Pilot

2.4.1. Description of Implemented Design

The Danish pilot is combining wind energy with tourism. One or two of the existing wind turbines, in total 20 turbines (Bonus today Siemens Gamesa each 2 MW from 2000), are used for visits.

20 years ago, the kind of visits were following an old Danish tradition made available at the annual wind day – 3rd Sunday in June – for the 8500 shareholders. Slowly, the possibility of visiting a wind turbine from the inside became known to universities and developers, and since 2012 the number of visits has slowly increased.

During the UNITED project period, the visits have been professionalized. Two boat operators are now having a visit on their tour program for tourism in Copenhagen. Therefore, three guides are now active. The Table 1 below is showing the increase of visits of the last years.

At the Danish pilot, two kinds of trips are organized:

- A simple trip with lecture getting 50 meters from the turbines; duration 2 hours.
- A trip including climbing to the turbine nacelle:
 - with Zodiacs duration 1½ hours;
 - With a boat having a stair in the front giving the opportunity of access from 4 different directions; duration 3-4 hours.

Table 1 – The turnover during the period 2017 – 2023; note that the indications for 2023 are those for only half a year

Business	2017	2018	2019	2020	2021	2022	2023
Trips	31	35	48	4	13	75	67
Guests	676	930	1117	130	246	1687	1569
1.000 €	38,9	44,3	55,6	4,4	19,5	102,1	111,7

The existing wind turbine owner – a cooperative with 8500 shareholders – has stipulated in its bylaw that the visits will be used to promote wind energy.

The visiting of the turbines is only possible, if:

- The wind turbine is of the old type from before 2007, where there are more floors in the turbine, so it is possible to climb without safety equipment (8 meters between the floors is the maximum).
- The visiting is only possible when the turbine owners allow it.
- Usually, no special investments are needed as the access to the turbine used by service providers is used. If boats of another type are used for the tourism, investments such as installation of a stair in the front of the ship may be needed.



Figure 8 – Example of stairs used for direct access to the foundation

In order to make use of the combination of wind energy farming and tourism in other countries, it is mandatory to make agreements with the owner of the wind turbine.

Comments: there may be an opportunity for establishing visits such as sailing around the wind turbines without entering the wind turbine. About half of the trips in Denmark is of this kind. Here, we are sailing in the sea where there are no restrictions, until a safety distance of 50 to 100 meters from the turbines.

We know that companies such as utilities and manufacturers of wind turbines have difficulties in accepting visits to their turbines. The reasons are conflicts between safety rules used by the people servicing the turbines and the safety rules used when having tourism. There is a difference as the turbines are not in operation when having tourism visits.

In some countries there are rules about sailing close to the wind turbines. As tourism must be done in close cooperation with the turbine owner, these rules are irrelevant. The tourism operator must be taken as part of the wind turbine organisation in the same way as an external service provider.

2.4.2. Costs

As the OWF used for the touristic activities is of an older and smaller scale, the potential to convert the inner working and make it safe for tourism, given the size and accessibility to shore, was not a major barrier. However, given the increasing size and distance from shore for new OWF installation, such conversion or adaptation is something which needs to be considered as they are often not suitable for such activities. The inclusion of tourism at the site did not yield additional cost saving measures for either of the activities. It is seen as a unique opportunity to increase the interest, education, and acceptance of OWF with the public and therefore, has an economic benefit beyond the financial gains in the operation of an additional tourism activities, namely, the potential to increase the acceptance and wide rollout of OWF.

2.4.3. Avoided Damages or Loss

There are two potential issues that have been identified during the turbine visits:

- 1) Loss from wrong treatment of the control system: This occurs when the control board is not returned to "remote control" from "local control." As a result, technical service providers need to physically access the turbine and reset the control system, so it can be used in "remote" mode again. To mitigate this issue, strict adherence to the "Training Manual" is crucial. Proper training ensures that the control system is handled correctly during visits, reducing the likelihood of unnecessary technical interventions.
- 2) Twisting of guests' foot by climbing the ladders in the turbine: Climbing the ladders in the turbine can sometimes lead to accidents, causing injuries like twisted feet. To prevent such incidents, visitors are required to strictly adhere to safety guidelines, which include wearing appropriate footwear. High heels and slippers are not allowed during visits to ensure proper foot protection. Additionally, the guides carry extra water to keep visitors hydrated, especially during warm weather conditions.

Furthermore, weather conditions can impact the feasibility of turbine visits. If the weather does not permit safe access to the turbines, the boat owners and guides may experience lost revenue due to canceled visits. Therefore, careful consideration of weather conditions is essential to optimize revenue and ensure the safety of visitors.

In summary, following the "Training Manual," strictly controlling footwear, and ensuring that the guests are hydrated are effective measures to mitigate the identified issues during turbine visits. Moreover, diligent weather monitoring helps avoid potential revenue losses for boat owners and guides by ensuring safe and enjoyable experiences for visitors.

2.4.4. Environmental Benefits

For the Danish pilot on the project, the environmental benefits of combining with farming with tourism are small. A potential benefit of combining these activities is the shared vessel use which leads to fewer boat trips. For the Danish pilot, however, this has shown not to be possible. In the first years of the pilot, few visiting trips used the service operator boat. However, it has turned out not to be possible for the long-term. When service

at the turbines is needed and possible urgent, the planning of incorporating a visit by tourists has shown not to be possible.

2.4.5. Uncertainty

One potential source for uncertainties is the weather, as it can make visits impossible:

- Thunder in a distance of less than 70 km makes a trip not possible.
- Too high wind speeds and waves can make a trip impossible.

Boats have to be maintained during periods where visits are not possible while for some times, boats are not available at all, as they are used for other tasks or break down.

Using the special Rigid inflatable boats (RIB) (Zodiacs) where you have to climb up the foundation directly from the water level is more uncertain than using a boat with landing stairs as shown on the picture in Figure 9.

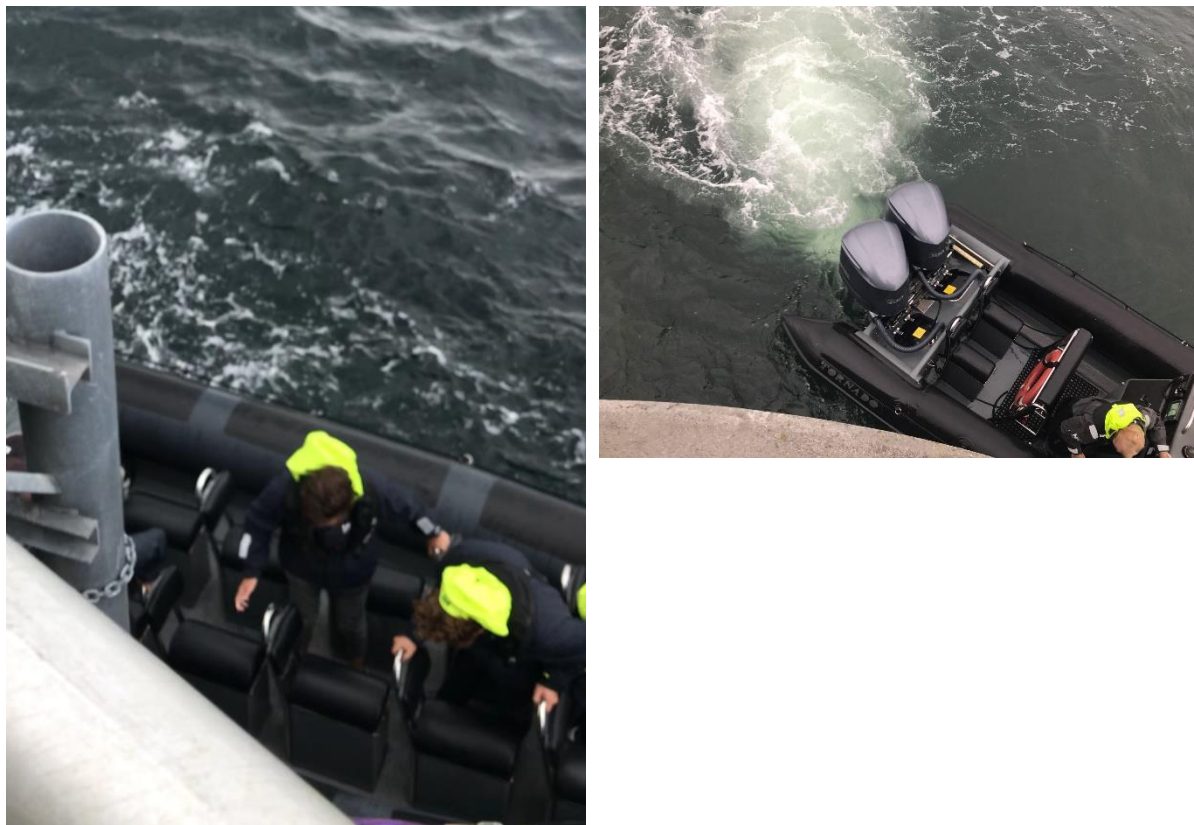


Figure 9 – RIB are more sensitive to the weather and ocean conditions

2.4.6. Robustness and Flexibility

The successful organization of turbine visits relies heavily on the turbine owner's willingness to temporarily close the turbine for 1 or 2 hours, with compensation provided for the power loss. Fortunately, the cooperative owner of 10 turbines promotes wind energy, and turbine visits are defined as a form of promotion, reducing the risk of interruptions.

To ensure long-term continuity, the Danish Energy Authority must grant a 25-year lease prolongation for the seabed. Without this extension, all activities would have to cease by 2025.

Accessing the turbine foundation from the sea level using Zodiacs presents challenges due to the ladder's location on the west side of the turbines. Wave and current movements become problematic at wind speeds exceeding 8-10 m/sec. However, improvements to the landing installation in summer 2023 aim to minimize visit cancellations.

Using a larger boat equipped with a special stair allows entry from four directions, providing better access even in winds up to about 15 m/sec. At higher wind speeds, boat owners typically suspend operations as it becomes challenging for guests to sail. However, access to only one boat with a front stair, due to deeper water requirements for other boats in the region, may lead to scheduling conflicts or visit cancellations if the boat is occupied or faces technical issues.

A potential bottleneck is the availability of skilled guides. The number of trips may not justify full-time positions, resulting in a possible shortage of qualified guides. Presently, three guides manage visits alongside their daily work, but two of them are retired individuals over 70 years old, raising concerns about the physical demands of climbing soon.

Visiting activities must be carefully coordinated with the technical service team's daily work, as turbine visits cannot occur during servicing. Overall, addressing these challenges ensures a smoother and more sustainable turbine visit experience.

2.4.7. Policy Cohesion

For The Danish Pilot, this section on Policy Cohesion is not relevant. If agreements with the wind farm owners are made, access to the sea is provided at all times. If there are no agreements, it is still possible to get close to the turbines as the rules permits.

2.4.8. Conclusions

The tourism activities and educational elements present in the Danish Pilot have achieved the highest TRL level possible and are operating as a commercial activity at the end of the UNITED project. The education outreach and site visits to the near-shore wind turbine at operating as a fully functioning venture at the Danish site, with additional tourism opportunities being explored and added to the offerings of the site. This has been proven to be suitable, beneficial to engaging society and increasing awareness of offshore energy, and a viable economic activity. The flexibility and scalability of such activities is not exceptionally large. Offering a large amount of such activities is not seen as a benefit as the current operations are able to handle the requests and demand for the area. Complications arise in the retrofitting and use of larger, newer wind turbine constructs as the losses incurred from the downtime during a visit are considerably larger, as is the difficulty in accessing the turbine itself. This would be a potential solution for smaller and/or older turbines which are able to facilitate such visit but widespread adoption and deployment could be difficult due to requirements in safety and practical considerations in terms of size and effort to execute such a visit.

2.5. Greek Pilot

2.5.1. Description of Implemented Design

The Greek Pilot, denoted as the PATROKLOS Pilot site, is situated in the 59th km of Athens-Sounio Ave., Palaia Fokaia, Attiki, Greece, in the wider area of Cape Sounio (Figure 7). The wider area is protected by NATURA 2000 and the Treaty of Barcelona due to a number of significant characteristics that this Pilot site has to offer. The area is a characteristic example of Mediterranean landscape. It includes an area declared a National Park since 1971 and is regarded as an archaeological site of great importance, furthermore 68% of the area is accessible and declared public. The current operator of the site is KASTELORIZO AQUACULTURE, a company that operates on the field of production, marketing and exploitation of fish farms with all kinds of fish, shellfish in fresh or



Figure 10 – Left and Middle: Pilot space, the yellow square depicts aquaculture unit (source : Google Earth). Right: Aquaculture unit and islet Patroklos on the opposite – Mediterranean Sea, Greece

frozen form as well as distribution of product at Greek premises and abroad. On the opposite of the aquaculture unit, there is an islet called “Patroklos”. The island, has a great coastline where local people as well as tourists from the wider Attica area, enjoy swimming and spending time on the beach. The project partner Planet Blue is a local diving center based in Lavrio, Greece, 60 km south of Athens and not far from Patroklos. Planet Blue has the full time equivalent of two employees and an annual gross turnover of 110 thousand Euro. They offer diving tours for groups and individuals. Planet Blue also has a business providing Remote Operating Vehicles (ROVs) to aquacultures, including mapping the underwater landscape of aquaculture sites or conducting inspections or repairs of aquaculture infrastructure placed in great depths. In addition, Blue Planet offers diving expeditions for cleaning up waste in the aquaculture area. Co-existence scenarios are facilitated with the use of WINGS’ monitoring and management platform, AQUAWINGS, that is deployed to ensure:

- Best multi-use of aquaculture and tourist activities
- Minimisation of environmental impact

The Greek pilot combines fish aquaculture and diving tourism. Hence in order for someone to investigate the aquaculture site underwater the respective visitor should be a certified diver. The trainings must have six theoretical sessions, six pool water sessions and four offshore diving sessions. Except for that the staff is also trained for the use of ROVs. People with no open water diver certification are not allowed to dive in the aquaculture site. Moreover, most professional divers are required by national or state legislation to be qualified as first aid providers to a specified standard as occupational health and safety are important aspects of professional diving. For the specific pilot, no extra training was required since the divers had already been trained for underwater investigation, which also includes the site of the aquaculture farm.

Within the Greek pilot aquaculture production parameters are monitored in real time. These parameters are salinity, temperature, Dissolved Oxygen (DO), pH, electrical conductivity, total dissolved solids (TDS), turbidity, Chlorophyll-a, Nitrates (NO₃) and ammonium (NH₄). Furthermore, the co-location activities connectivity is monitored, and the aquaculture infrastructure by using underwater sensors, fish sensors, water quality sensors and meteorological sensors. Also, the sea transportations infrastructure is monitored (vessel movements and speed, meteorological sensors). By the use of underwater cameras, the fish behaviour and performance is monitored. Monitoring infrastructure continues in diving activities by using individual diver position sensor, mechanism for unexpected surface event such as rapid weather change or another incident. For the aquaculture infrastructure that are placed in great depths (such as anchors) a ROV is used. A Real-time data management and decision support system is in place and the water quality data are being uploaded continuously in real time in the AQUAWINGS platform where the users of the pilot can have access to them. The AQUAWINGS platform was co used in the pilot for the planning of different activities that take place in the aquaculture farm e.g. diving and feeding. Fish behaviour was continuously monitored through cameras in order to check the fish stress when diving activities were taking place.

The most important parameters monitored concerning fish aquaculture are: dissolved oxygen, water temperature, ammonia, and of course the number of tourist divers is also of great importance.

2.5.2. Costs

The Greek pilot on ocean multi-use entails several implied costs that were encountered during its implementation:

Firstly, there was a need to invest in low-cost and environmentally friendly cameras and sensor installations powered by solar panels. This required initial investments in research, development, and the procurement of suitable equipment. The aim was to ensure a sustainable and eco-friendly approach to data collection and monitoring.

Secondly, a transition to wireless data transmission was pursued to enable independent data transmission to the cloud, eliminating the reliance on wired connections. This process involved upgrading existing infrastructure or adopting new technology, incurring associated costs. Another significant cost arose from the replacement of inadequate cameras that experienced technical malfunctions and damage due to challenging underwater conditions and high currents of seawater. Upgrading to better-performing alternatives, such as the Imenco Labrus Shark underwater cameras, incurred additional expenses. Furthermore, the pilot sought to expand its data collection and validation efforts to other geographical areas like Epidavros, Igoumenitsa, and Korinthian Gulf. However, this expansion involved expenses related to equipment deployment, logistics, and data processing in those regions. By conducting tests under diverse conditions, we were able to capture a wide range of environmental factors and their impact on fish behaviour and aquaculture activities. Utilizing the same camera system across different areas allowed us to establish consistent data collection protocols, enhancing the reliability and credibility of the information gathered. Furthermore, the incorporation of data from these additional locations provided valuable baseline conditions and comparative insights, enabling a more comprehensive understanding of the aquaculture environment. This multi-site approach also facilitated the development and optimization of our camera systems, ensuring their effectiveness and performance during both the pre-operational and operational phases of the project.

Moreover, the Coronavirus crisis and related travel restrictions have significantly impacted both multi-use partners. Planet Blue reliance on tourism, has suffered due to reduced travel and visitor numbers. As a result, the revenue from tourism-related activities, including scuba diving expeditions, has been affected. This situation has implications for the pilot's financial sustainability and may require adjustments to operational strategies during times of crises.

2.5.3. Avoided Damages or Loss

Firstly, the use of advanced cameras and sensors in aquaculture sites and touristic areas enable improved environmental monitoring. By closely monitoring fish behaviour, water quality, and environmental conditions, the pilot can swiftly detect any anomalies or issues. Early detection helps prevent potential environmental damage or loss, as prompt actions can be taken to address emerging challenges.

Secondly, transitioning to low-cost and reliable wireless data transmission ensures enhanced safety and reliability in data collection. By eliminating the reliance on wired connections, the risk of disruptions caused by operating vessels or external factors is significantly reduced. The continuous and efficient data collection process minimizes the chances of data loss and ensures the availability of crucial information for decision-making.

Last but not least, the improved public perception of aquaculture through the diving activities can foster positive relationships with local communities and reduce the risk of opposition to the aquaculture farm's presence. By enhancing social acceptance, the pilot avoids potential conflicts and reputational damages.

2.5.4. Environmental Benefits

By sharing the same marine space for aquaculture and tourism activities, the pilot promotes efficient use of resources and reduces the overall environmental footprint. This approach helps minimize the physical footprint of both sectors, leading to less habitat disruption and preserving the natural environment. Moreover, the combination of aquaculture and tourism activities can create artificial reefs around aquaculture structures, attracting marine life and supporting increased biodiversity. The presence of fish farms can create a thriving ecosystem, providing food and shelter for various marine species.

Furthermore, the pilot's focus on innovative technologies and monitoring parameters improves the efficiency and effectiveness of aquaculture operations. Sustainable aquaculture practices ensure responsible fish farming

with minimal impact on surrounding ecosystems. By closely monitoring parameters such as fish behaviour, stress levels, water quality, and other environmental factors, the pilot can optimize production conditions. This leads to more sustainable aquaculture practices and reduces the environmental impact of fish farming. Additionally, by utilizing innovative technologies and wireless data transmission, the pilot reduces the ecological footprint associated with monitoring activities. The use of solar panels for energy supply promotes renewable energy adoption and decreases reliance on traditional power sources, contributing to a more sustainable operation.

Lastly, through tourism activities, visitors have the opportunity to observe aquaculture operations and learn about the importance of sustainable practices. This increased awareness fosters a sense of responsibility for marine conservation among tourists and local communities. By demonstrating the feasibility and benefits of ocean co-sharing for aquaculture and tourism, the pilot sets an example for future projects in the region. This can lead to the development of more sustainable and environmentally friendly initiatives in the long run.

2.5.5. Uncertainty

The Greek pilot faces uncertainties related to economic feasibility challenges, opportunity costs, and balancing value and expectations with costs. The costs associated with staff, insurances, and permits need to be carefully assessed to ensure the pilot's economic viability. There may be uncertainties regarding the acceptance and development of the aquaculture unit, as well as the contribution of touristic attractions to the growth of the wider area and local business expansion. Additionally, uncertainties may arise from the planning actions, including the implementation of monitoring infrastructure and real-time data management systems. In addition to the existing uncertainties, the Greek pilot also faces uncertainties caused by the economic crises, including the impact of COVID-19 restrictions. The COVID-19 restrictions posed significant challenges in carrying out touristic activities during the operational period. However, once the lockdown restrictions were lifted, the pilot managed to resume touristic expeditions, albeit at a reduced capacity. The lower number of tourist diving activities, approximately 60% lower than before COVID-19, reflects the uncertainties and fluctuations in tourism demand during these exceptional circumstances.

2.5.6. Robustness

To address disruptions to farming operations and ensure robustness, the pilot needs to implement measures that minimize disruptions, such as the monitoring infrastructure in aquaculture, sea transportation, and diving activities. By monitoring individual diver positions and having mechanisms in place for unexpected surface events, the pilot aims to maintain undisturbed and safer diving activities. The use of real-time data management and decision support systems can also enhance the robustness of the pilot by providing timely information for effective decision-making. The Greek pilot demonstrates resilience and adaptability in the face of the economic crisis. Despite the challenges posed by COVID-19 restrictions, the pilot successfully resumed touristic expeditions once the restrictions were lifted. However, the reduced number of tourist expeditions indicates the need for continuous monitoring and adjustments to ensure the robustness of the pilot's operations. The pilot has also witnessed changes in diving patterns, with an increase in shore diving and a decrease in boat diving due to increased fuel charges and commuting expenses.

2.5.7. Flexibility

The pilot aims to achieve flexibility through the co-use of transportation and offshore experience. By exploiting the same marine space, the pilot can optimize resource utilization and increase operational flexibility. Additionally, the improvements in aquaculture equipment, infrastructure, management, and monitoring systems indicate a willingness to adapt and evolve based on the changing needs and demands of the pilot. Moreover, the Greek pilot has shown flexibility in response to the economic crisis and its associated challenges. The pilot managed to adjust its operations and continue with touristic expeditions once the COVID-19 lockdown restrictions were withdrawn. The observed shift from boat diving to shore diving reflects the pilot's flexibility to adapt to increased fuel charges and the need to reduce diving fees for local divers. This flexibility allows the pilot to optimize operations and cater to the changing preferences and financial considerations of divers.

2.5.8. Policy Cohesion

The spatial planning approach in Greece is primarily sector-focused rather than area-based, resulting in fragmented maritime spatial planning (MSP). Several Special Frameworks for Spatial Planning at the national level exist, which provide guidelines for specific sectors such as aquaculture, renewable energy, industry, and tourism. However, there is no overarching, integrated policy approach for marine areas, leading to fragmentation in MSP.

The fragmentation in MSP may hinder the implementation of certain technological solutions. The lack of a comprehensive, area-based approach makes it challenging to incorporate multiple activities and interests within a given marine space. The sectorial nature of spatial plans, such as the aquaculture plan that promotes zoning of the sea for aquaculture, often focuses on avoiding interferences with other activities rather than embracing multi-use (MU) concepts. This sectorial character of spatial plans can impede the seamless integration of technical solutions that require coordination and cooperation among various stakeholders.

Moreover, the ad hoc decision-making process for MU in Greece implies that the allowance of MU can vary from site to site. While initiatives of MU exist in Greece, such as the fishing tourism activities and the Greek pilot case involving fishing farm and tourist diving, there is no guarantee that the same technical solution can be easily implemented at other sites. The decision on whether or not to allow MU may differ for different locations, depending on specific circumstances and considerations.

The involvement of multiple authorities in the establishment and operation of fish farms, including agencies responsible for spatial planning, environmental protection, health protection, tourism, and nature conservation, as well as local authorities, can create challenges and potential delays in implementing certain technical solutions. The requirement to consult and obtain approvals from various agencies adds complexity and may hinder the efficiency of the implementation process.

2.5.9. Conclusions

The touristic activities coupled with the fin-fish aquaculture activities executed within the UNITED project have reached a commercial viability and are proven to work and operated successfully in the given environment. The benefits of additional monitoring potential for the area at large (in consideration of where diving trips are executed) and the societal awareness and education in seeing how such fin-fish aquaculture construct operate is deemed a success. The concept and require technologies to facilitate such combined activities are readily adaptable to other conditions and locales, making such a multi-use solution viable in a broad spectrum of site cases. The increased offering of site locales for diving companies, underpinned by the educational nature of such visit and exposure of the general public and enthusiasts to via and learn more about food production in the marine environment is quite beneficial as the opportunity to do so on site is seldom available, leaving an industry which accounts for 21% of the European aquaculture sector by volume, a total of 267.7 thousand tonnes of fish as of 2020, a mysterious processes for many consumers (https://oceans-and-fisheries.ec.europa.eu/ocean/blue-economy/aquaculture/overview-eu-aquaculture-fish-farming_en). With the sectors poised to expand in coming years, increasing marine and aquaculture literacy and understanding is crucial to have societal acceptance and critical consideration of the practices supplying foodstuffs for the European population.

3. ASSESSMENT SYNTHESIS AMONG PILOTS

3.1. Generalised Benefits

Generalized benefits of multi-use offshore aquaculture systems encompass a wide range of advantages that extend beyond specific factors or individual components. These benefits contribute to the overall sustainability and efficiency of these integrated systems, and encompass both directly tangible benefits, such as increase in productivity, the reduction of costs, or enabling of commercialisation of activities but also intangibles such as the increase in available space, auxiliary environmental benefits and more. One of the key generalized benefits is the optimized utilization of limited ocean space. By combining multiple activities such as aquaculture, wind farms, and tourism, multi-use offshore systems more efficiently utilise the increasingly scarce amount of marine space. As the maritime, energy, fishing, nature conservancy, and other sectors compete for sufficient access to optimal areas for their activities, these sectors increasingly come into conflict as the optimal zones can often overlap, with closeness to shore and accessibility being a key factor in costs and commercial viability. This efficient use of space helps to alleviate the pressure on coastal and offshore resources.

Another significant benefit is the promotion of biodiversity and conservation efforts. Multi-use offshore aquaculture systems can serve as artificial reefs, providing shelter and habitat for various marine species. They can also be integrated into marine protected areas, contributing to conservation goals and enhancing biodiversity. Additionally, these systems offer opportunities for economic diversification and job creation. By integrating different activities, such as aquaculture and tourism, multi-use offshore systems can stimulate local economies, generate employment opportunities, and contribute to coastal community development.

Environmental sustainability is a crucial generalized benefit. Multi-use offshore aquaculture systems can play a role in mitigating eutrophication by removing excessive organic matter from the water column. They can also serve as carbon sinks, absorbing and sequestering carbon dioxide from the atmosphere. Furthermore, these systems promote innovation and technological advancements. The integration of various activities requires the development of new technologies, monitoring systems, and operational practices. This drives research and development, fostering innovation within the aquaculture and renewable energy sectors.

3.1.1. Costs

The economic performance of the solutions has been thoroughly assessed, taking into consideration various cost aspects. The report focusses onto the evaluation of whether the new design offers cost advantages in terms of building, maintaining, deploying, and repairing the implemented solutions.

In ensuring the economic acceptability of the pilot implementations, valuable insights from deliverables 3.3 and 3.4 are leveraged. These outputs clarify the economic feasibility of the proposed solutions, enabling a comprehensive evaluation of their economic performance.

Taking a closer look at each of the pilots:

- German Pilot: A feasibility study was conducted to ensure the economic viability of commercial aquaculture systems at the location FINO3 before the UNITED project (Geissler et al. 2018). This study likely considered cost factors to gauge the financial sustainability of the pilot implementation.
- Dutch Pilot: The pilot was successfully carried out within the allocated project budget. However, there were instances of increased prices due to unforeseen events such as the pandemic or the inflation. Despite this, there is optimism for future scalability, with the expectation that it will become commercially interesting.
- Belgian Pilot: The feasibility study for the Belgian pilot assessed financial aspects, including infrastructure and operational costs, while considering potential revenue streams and market demand to determine the commercial viability of multi-use offshore aquaculture systems.
- Danish Pilot: No key facts on costs have been provided for the Danish Pilot. The absence of cost-related information is due to the expenses being managed by external boat operators.
- Greek Pilot: The Greek Pilot involved investments in measurement devices. However, the revenue from tourist-related activities was affected by the pandemic, which had implications for costs.

A summary of the cost assessment of the pilots can be seen in the table below.

In conclusion, understanding the costs associated with each pilot implementation is vital to comprehensively assess their economic performance. While some pilots have provided key facts on costs, others may require additional data and analysis to fully evaluate their economic acceptability. Again, the reader is referred to deliverables 3.3 and 3.4 for more detailed information on economic aspects of the pilots.

Table 2 – Summary of cost assessment of the pilots

Pilots	Costs		
	Economic viable	Increased prices	Absence of tourists during pandemic
German	X	X	
Dutch	X	X	
Belgian	X	X	
Danish			X
Greek			X

3.1.2. Avoided Damages or Loss

The assessment of expected improvements in terms of safety and security, leading to avoided damages or loss, is a crucial aspect of evaluating the economic performance of the pilot implementations.

- **German Pilot:** To ensure safety and security, simulations to identify potential vulnerabilities and assess the system's overall performance were done for the German Pilot. Based on the findings, the design is optimized and adjusted as needed. Physical testing nearshore allowed for further adjustments and modifications to enhance safety. Once the necessary optimizations are made, the deployment of the solution takes place offshore. Continuous data collection through monitoring allows for ongoing refinements to ensure safety and mitigate the risk of damages or loss.
- **Dutch Pilot:** In the Dutch Pilot, safety and security are addressed through careful design considerations. Remote monitoring helps in real-time tracking and prompt responses to any anomalies, reducing the risk of damages or loss. Regular inspections and maintenance practices are part of the operational and management efforts to ensure safety and avoid potential damages.
- **Belgian Pilot:** To mitigate risks and avoid damages in the Belgian pilot, various measures were implemented, including anchoring methods, detailed activity planning, modeling, nearshore tests, strategic placement away from cables, evaluation by external consultants, and the use of pingers for easy retrieval in case of detachment. These precautions aimed to ensure the effectiveness and reliability of the integrated aquaculture system within the windfarm.
- **Danish Pilot:** In the Danish pilot, avoiding damages or loss is achieved by following safety guidelines, wearing appropriate footwear, and staying hydrated during turbine visits. Training material is provided to ensure visitors are aware of safety protocols. Additionally, careful weather monitoring prevents revenue loss due to cancellations.
- **Greek Pilot:** Here, monitoring through data collection plays a significant role in ensuring safety and security. Additionally, the engagement in tourist activities is conducted which helps people to understand the activities.

In conclusion, the assessment of expected improvements in safety and security measures is essential to avoid damages or loss in the course of implementing pilots. The summarised findings can be found in the table below.

Table 3 – Summary of avoided Damages or Loss of the pilots

Pilots	Avoided Damages or Loss			
	Simulations	Physical or near-shore testing	Remote monitoring and data collection	Inspections
German	X	X	X	X
Dutch			X	
Belgian	X	X	X	X
Danish				
Greek			X	

3.1.3. Environmental Benefits

Here, the summary of the environmental benefits associated with each solution implemented in the pilots is given. Table 4 shows the consolidation. Note that further details and information can be found in deliverables 8.3 and those of WP4.

- Multi-Use Low Trophic Aquaculture:** Implementation of low-trophic aquaculture results, in the applied cases, food stuffs for human consumption, high value products from algal processing, construction materials and a myriad of other application for the algae species, mussels, and oyster considered. This yield does not require the input of extra of external nutrients, but rather act as a nutrient sink in eutrophic waters, thereby bettering the environmental status of degraded waters. This extraction of excess nutrients is a key factor in the implementation of LTA and can be seen as a remediation effort to enhance the quality of these waters. While the smaller implementation of pilot scale activities means it is hard to quantify exact effects, further investigation using the growth potential is required in order to determine impacts as scale. Through the combination of these activities within wind farms, the demand on marine space is limited, thereby allowing for the expansion or creation of the activities within planned and operating OFWs, allowing for additional space to be allocated and protected for nature. Furthermore, the shared use of vessels, or potential use of electrified vessels, decreased carbon emissions and also the number of vessels required to accommodate the commercial activities, also lowering marine noise causes from vessels and spread activities. The aquaculture aspect of the pilots introduces additional structures which creates shelters and introduces hard substrate into regions where they are not present. While this can be considered habitat manufacturing, following nature inclusive design principals and guidance from ecologists and biologists, designed structures can be introduced at locations where they are beneficial and enhancing to the local environment in a manner which is overall positive. This facet does need to be carefully considered as it can be easily manipulated in a form of greenwashing which is not overall beneficial to the local environments, and whose benefits can be negated once the service life of the structures is completed and they are removed, effectively destroying introduced or recreated habitats. This multi-use approach also leads to more available space for nature conservation.
- Floating Solar:** The use of solar energy contributes to a cleaner and greener energy source, reducing environmental impact and increasing the production potential to coastal communities and densely populated coastal areas without the requirement of highly demanded land surface area. Additionally, since in many cases the transmission infrastructure for energy is already present within OWFs, the need install additional transmission infrastructure is mitigated, and the losses from transmission from remote areas on land suitable for solar farms is also avoided.
- Tourism:** Through the integration of tourism alongside existing marine activities, the awareness of these processes and activities, often not seen or understood from the public due to their remote nature, is better brought to light for the public and interested parties. This has multiple benefits, where the presence of public and interested or invested parties increases awareness, education, and acceptance potential of these offshore activities. Additionally, combining monitoring with touristic trips enhances the overall monitoring regime of environmental aspects.

In conclusion, the assessment of environmental benefits associated with each pilot highlights the positive contributions of multi-use approaches, solar energy utilization, and improvements in marine biodiversity and water quality.

Table 4 – Summary of Environmental Benefits of the pilots

Pilots	Avoided Damages or Loss				
	Improved water quality	Improved biodiversity	Efficient use of space & freed space	Shared vessel use	Renewable energy source (monitoring)
German	X	X	X	X	
Dutch	X	X	X		X
Belgian	X	X	X	X	
Danish					
Greek	X	X			X

3.1.4. Uncertainty

The assessment of uncertainty areas is crucial to understanding the potential challenges and risks associated with the implementation of the pilots in this project. Each pilot has identified specific uncertainty areas that require attention and mitigation strategies. Here, a small summary is given of the information on uncertainties from section 2 and a comparison of pilots in the Table 5 below.

- **German Pilot:** The German pilot has identified several uncertainty areas, including the assessment of the environmental impact of the implemented systems, as the impacts of the aquaculture systems on the environment are yet not fully known. This involves understanding the potential effects (also positive ones) on marine habitats and biodiversity. Additionally, the establishment of standardized regulatory frameworks, guidelines, and policies is essential to ensure smooth operations and compliance with regulations. Public acceptance and perception of the pilot's activities are also critical, as community support plays a significant role in the success of such projects. Offshore aquaculture was unknown and not present in the public. The German pilot contributed significantly to a positive public acceptance by numerous dissemination activities especially a TV documentary which reached several millions people and lots of requests for a further documentary on this topic (is made in summer 2023 and will be broadcasted in fall 2023).
- **Dutch Pilot:** Similar to the German pilot, the Dutch pilot also faces uncertainties related to the environmental impact of the systems. Additionally, offshore operations come with inherent uncertainties, particularly due to weather dependencies. Weather conditions can impact the safety and efficiency of operations, necessitating careful planning and adaptability.
- **Belgian Pilot:** In the Belgian pilot, uncertainties encompass environmental implications, economic feasibility, regulatory frameworks, unpredictable weather, unexpected costs, and global events like the COVID-19 pandemic. Proactive measures, including designing upscaled scenarios, adhering to safety protocols, and adapting to unforeseen challenges, underscore the project's commitment to addressing uncertainties for sound environmental management, investor confidence, and long-term sustainability.
- **Danish Pilot:** The Danish pilot faces uncertainties related to weather conditions, which may make visits impossible at times. The maintenance of boats is another area of uncertainty, as there could be occasions when boats are not available for use due to maintenance needs. Moreover, the design of the boat, especially the choice between climbing and landing stairs, introduces uncertainties related to accessibility and safety.
- **Greek Pilot:** The Greek pilot encounters uncertainty areas concerning economic feasibility. Balancing the value and expectations with the costs is a critical aspect that requires careful consideration. The acceptance and development of aquaculture practices also pose uncertainties, as community engagement and market acceptance play significant roles. Additionally, uncertainties arise from planning actions, implementing monitoring infrastructure, and managing real-time data. Economic crises, such as the COVID pandemic, introduce additional uncertainties that may impacted the pilot.

In conclusion, understanding and addressing uncertainty areas are essential for the successful implementation of the pilots. These uncertainties include environmental impact assessment, regulatory frameworks, weather dependencies, economic feasibility, community acceptance, and operational challenges. Mitigation strategies and adaptive measures are vital to overcoming these uncertainties and ensuring the overall success of the projects.

Table 5 – Summary of Uncertainty Areas of the pilots

Pilots	Areas of Uncertainty							
	Environmental Impact of Systems	Framework, guidelines, policies	Public acceptance and perception	Weather and ocean conditions	Availability of boats/vessels	Design of boats/vessels	Economic feasibility and costs	Crises (pandemic, inflation, ...)
German	X	X	X	X	X	X		X
Dutch				X				X
Belgian	X	X	X	X	X	X	X	X
Danish				X	X	X		X
Greek				X			X	X

3.1.5. Robustness

The concept of robustness is a significant consideration in the pilots, ensuring their ability to withstand adverse and rough weather conditions and offshore environments.

- German Pilot: The German pilot emphasizes the importance of robustness in facing adverse and rough weather conditions and offshore challenges. This robustness ensures the smooth functioning of the implemented systems, even under challenging environmental circumstances.
- Dutch Pilot: Similar to the German pilot, the Dutch pilot prioritizes robustness in the face of adverse and rough weather conditions that are common in offshore environments. The ability to withstand such conditions is crucial for the sustained operation of the pilot solutions.
- Belgian Pilot: In the Belgian nearshore aquaculture systems, the venture demonstrated robustness through adaptive measures, such as transitioning from vulnerable open frame basket systems to secure closed cages, fortifying seaweed net connections for offshore stability, and addressing challenges by incorporating tracking devices. Despite setbacks, the resilience of restoration cages remained consistent, validating their efficacy in both nearshore and offshore environments.
- Danish Pilot: In the Danish pilot, the robustness of turbine visits relies on the turbine owner's cooperation to temporarily close the turbine for 1 to 2 hours, ensuring safe access for visitors. Additionally, obtaining a 25-year lease prolongation is crucial for the pilot's long-term sustainability, as an extension is needed to continue operations beyond the current lease agreement.
- Greek Pilot: In the Greek pilot, robustness is ensured through various measures to minimize disruptions. These measures include the implementation of monitoring systems for continuous evaluation, efficient sea transportation practices, and safe diving activities. The real-time data management and decision support systems (DSS) also contribute to the robustness of the project. Moreover, the pilot demonstrates resilience and adaptability during crises such as the COVID pandemic and periods of increased prices. Notably, the pilot successfully resumed touristic expeditions after facing the challenges of the pandemic, highlighting its robustness in dealing with unforeseen circumstances.

In conclusion, robustness is a critical factor in the pilots, particularly in the face of adverse weather and offshore conditions. The ability to withstand such challenges ensures the sustained and efficient operation of the implemented solutions. Below, the table gives a short summary among the pilots.

Table 6 – Summary of Robustness assessment of the pilots

Pilots	Robustness	
	Weather	Crises (resilience & adaptability)
German	X	
Dutch	X	
Belgian	X	
Danish	X	
Greek	X	X

3.1.6. Flexibility

Flexibility plays a vital role in the pilots, enabling optimized resource utilization, efficient allocation of ocean space, and adaptability to changing conditions. A summary for the pilots is shown in Table 7.

- **German Pilot:** The German pilot emphasizes flexibility through various aspects of its implementation. The modular nature of the systems allows for scalability and adaptability, facilitating the expansion and integration of new technologies and practices as needed. Adaptive management is another essential aspect, enabling dynamic decision-making based on real-time data. Adjustments to optimize performance and minimize environmental impacts can be made, ensuring sustainable development.
- **Dutch Pilot:** In the Dutch pilot, flexibility is evident in the design of structures, ensuring they are flexible enough to resist impacts, particularly in challenging offshore environments. The operational aspects are also guided by flexibility, with work planned according to weather conditions to maximize safety and efficiency. The adaptability of staff and the organization allows for responsive actions to changing circumstances. Furthermore, the seaweed industry's inherent flexibility enables the project to leverage opportunities and overcome challenges.
- **Belgian Pilot:** Flexibility is a central element in the Belgian pilot, evident in the aquaculture structures designed to gracefully adapt to water motion, the agile operations of the crew responding to varying weather conditions, adaptive resource allocation for efficient responses to changing project needs, and environmental monitoring guiding strategic decisions for optimal installation times. This flexibility is crucial in successfully integrating oyster and seaweed aquaculture with oyster restoration in the dynamic offshore wind farm environment.
- **Danish Pilot:** Flexibility is paramount in the Danish pilot, as weather conditions and boat limitations play a significant role in planning turbine visits. The availability of suitable equipment on boats, such as stairs for safe entry, also impacts visit flexibility. Moreover, the number of skilled guides presents a bottleneck. To accommodate visits, the schedule must align with the daily work of the technical service team, ensuring smooth operations without interrupting turbine servicing. Adapting to these factors ensures a successful and flexible turbine visit experience in the Danish pilot.
- **Greek Pilot:** In the Greek pilot, flexibility is demonstrated through continuous improvements in equipment, management practices, infrastructure, and monitoring systems. The willingness to adapt and evolve ensures that the project remains responsive to changing circumstances and emerging opportunities. The pilot also displays flexibility in response to crises and their challenges, as evidenced by their shift from boat diving to shore diving in response to increased fuel prices.

In conclusion, flexibility is a key characteristic of the pilots, enabling them to optimize resource utilization, adapt to changing conditions, and respond to challenges effectively. The modular and adaptable nature of the systems, coupled with data-driven decision-making, contribute to the successful implementation of the projects while promoting sustainability and environmental stewardship.

Table 7 – Summary of Flexibility assessment of the pilots

Pilots	Flexibility				
	Optimised use of resources and space	Flexible Structure / Modular System	Flexible Operation	Flexible Organisation	Change of locations
German	X	X	X	X	
Dutch	X	X	X	X	
Belgian	X	X	X		
Danish			X	X	
Greek		X			X

3.1.7. Policy Cohesion

Policy cohesion is a critical aspect of the pilots, ensuring that they align with established guidelines and regulations. To achieve this, the summarised outputs of deliverables 6.1 and 6.2, along with the information gathered from the WP6 workshop held in November 2022, are integrated into the evaluation process.

- German Pilot: In Germany, the evaluation of technical solutions requires thorough consideration, as policies do not explicitly address the MU of seas. The absence of clear regulations leads to uncertainty and financial feasibility challenges for MU activities. Additionally, insuring against the loss of aquaculture products is deemed unfeasible without appropriate policies and guidelines in place.
- Dutch Pilot: In the Netherlands, the pilot holds permits for testing innovations, demonstrating adherence to regulatory requirements. Moreover, Dutch policy dictates that every new offshore wind farm (OWF) must be open to multi-use activities. The existence of a Dutch working group dedicated to multi-use further reflects the commitment to policy cohesion and coherence.
- Belgian Pilot: In establishing a policy framework for multi-use offshore projects in Belgium, considerations include tailored environmental regulations within the Marine Spatial Plan, prioritizing community engagement for local acceptance, adapting economic feasibility policies to Belgium's financial landscape, emphasizing safety and adaptability to weather conditions, and recognizing the importance of policy flexibility in navigating global crises such as the COVID-19 pandemic and energy challenges.
- Danish Pilot: The Danish pilot acknowledges the necessity of agreements with wind farm owners to enable visits to their offshore structures. This highlights the importance of policy alignment and cooperation between stakeholders to facilitate multi-use activities.
- Greek Pilot: In Greece, the planning is primarily focused on sector/single-use activities, which presents challenges for multi-use implementation. The varying allowances for multi-use activities from site to site indicate the complexities of navigating multiple authorities and policies.

In conclusion, policy cohesion and coherence are essential considerations for the pilots to ensure a thorough evaluation and successful implementation. Integrating the outputs of relevant deliverables and workshops helps establish policy consistency, enabling the effective implementation of multi-use solutions in the marine environment. Table 8 shows a summary among the pilots for policy coherence.

Table 8 – Summary of Policy Cohesion for the pilots

Pilots	Policy Cohesion	
	No MU plans from government	MU implemented in government plans
German	X	
Dutch		X
Belgian		X
Danish		
Greek	X	

3.2. Operationalising in Practice

Operationalizing multi-use offshore aquaculture systems in practice involves several key considerations to ensure successful implementation. Site selection plays a crucial role, identifying suitable locations that meet the requirements of different activities. Design and engineering must be tailored to specific needs, optimizing space utilization and minimizing conflicts. Effective management and monitoring practices are vital, including regular assessment of water quality, environmental impacts, and production parameters. Collaboration and coordination among sectors and stakeholders foster integration and shared resources. Knowledge sharing and capacity building ensure the necessary skills for managing these systems. Continuous research and development efforts drive technological advancements and sustainable practices. By addressing these considerations, multi-use offshore aquaculture systems can be operationalized effectively, leading to sustainable and integrated operations in coastal and offshore environments.

3.3. Support Required for Adoption

The successful adoption of multi-use offshore aquaculture systems requires various forms of support to overcome challenges and facilitate implementation.

- **Financial support:** Adequate funding is crucial to cover the initial setup costs, infrastructure development, technology acquisition, and operational expenses associated with multi-use offshore aquaculture. Financial support can come from public funding, private investments, grants, and subsidies to encourage the adoption of these systems.
- **Research and development:** Continued research and development efforts are necessary to improve system design, operational practices, and technology. Support for research institutions, universities, and industry collaborations can drive innovation, address technical challenges, and enhance the overall performance of multi-use offshore aquaculture systems.
- **Policy and regulatory frameworks:** Well-defined policies and regulatory frameworks are needed to provide clarity, guidance, and a supportive environment for the adoption of multi-use offshore aquaculture. Governments and regulatory bodies should establish streamlined permitting processes, spatial planning guidelines, and environmental impact assessments specific to these systems.
- **Knowledge sharing and capacity building:** Supportive initiatives that promote knowledge sharing, capacity building, and technical training are crucial for operators, stakeholders, and local communities. Educational programs, workshops, and networking opportunities can enhance understanding, skills, and awareness regarding multi-use offshore aquaculture systems.
- **Stakeholder engagement:** Engaging with stakeholders, including coastal communities, environmental organizations, and industry representatives, is essential to gain their support, address concerns, and foster collaborative decision-making. Public consultations, information campaigns, and participatory processes can facilitate the adoption and acceptance of these systems.
- **Infrastructure and technical support:** Access to suitable infrastructure, such as ports, processing facilities, and research laboratories, is essential for the successful adoption of multi-use offshore aquaculture systems. Technical support, including monitoring equipment, data management systems, and operational assistance, can also contribute to the smooth functioning of these systems.
- **Market development and marketing support:** Efforts to develop markets and promote the products of multi-use offshore aquaculture, such as sustainably farmed seafood and renewable energy, can boost the economic viability of these systems. Market development initiatives, marketing support, and certification programs can help create demand and ensure the success of the products derived from these systems.

By providing comprehensive support in the areas of finance, research, policy, capacity building, stakeholder engagement, infrastructure, and market development, the adoption of multi-use offshore aquaculture systems can be facilitated, leading to sustainable and integrated operations in coastal and offshore environments.

4. CONCLUSIONS

The European Environment Agency has regularly reported that the condition of European Waters is continually at risk, and the resultant pressures from currently realised and planned activities in European Seas is increasingly placing them under a wide spectra of pressures (EEA, 2021). Meanwhile, the need to conserve and protect marine space is underpinned by the EU Mission to Restore our Oceans and Waters² which highlights the need for initiatives to reduce the negative impacts maritime and marine activities are having on global seas; particularly the heavily utilised European Waters. The expanding use of marine waters is unlikely to decrease in the near future, therefore a prerequisite for responsibly realising these ambitions relies on innovative and environmentally responsible solutions to enhance the quality of these water as we increase our presence. The pilots and activities undertaken in the context of the UNITED project elucidates that there is considerable theoretical potential for offshore aquaculture, particularly low-trophic aquaculture, in light of the planned expansion for offshore wind energy use. However, the realization of this potential is contingent upon forging agreements with wind energy operators on corresponding joint uses, support from policy and licensing agencies, and a need to preserve and enhance the natural resources in European Waters responsibly. This is indicative of a developing symbiotic relationship between the multiple sectors and underscores the importance of early-stage planning and collaboration in order to realise economic benefits for the sectors involved, nature restoration, and the betterment of European Seas. Despite the theoretical potential, the short-term immediate scaled implementation of such projects looks to be currently unlikely as reported by NASTAQ 2020; through initiatives and developments such as those undertaken in UNTIED, this is hoped to change. There are a myriad of reasons that such endeavours have not yet been implemented, including ship safety, nature and marine protection, and concerns regarding profitability. These challenges present significant hurdles to the immediate realization of offshore aquaculture projects, necessitating a thoughtful and strategic approach to overcome them. Multifaceted benefits of systems that integrate mussels and algae, floating solar, and nature restoration can provide important ecosystem services through the extractive effect of inorganic and organic emissions, lowering of carbon based fuel reliance, and both the enhancement and preservation of natural systems. Moreover, they have the potential to increase economic stability due to the diversification of incomes and contribute to enhancing social acceptance. This suggests that, despite the challenges, there is a silver lining that points towards the potential benefits of pursuing such integrated multi-use efforts.

The environmental benefits of multi-use offshore systems have been shown in the Pilot and confirmed, assessed, and validated across various scientific publications. The conservation of biodiversity, enhanced fish populations, improved water quality, and reduced environmental impact have all been confirmed through scientific research and studies. These assessments provide robust evidence supporting the efficacy and sustainability of multi-use offshore aquaculture in addressing environmental challenges while meeting the growing demands for food, energy, and tourism in a responsible manner. As many of the pilots are small scale operations deployed in order to prove concepts and raise TRL levels, allowing for future scaling and roll-outs, the broader effects of such scaled deployments require monitoring and critical modelling to be done prior to large scale deployment to ensure that marine health is safeguarded.

Touristic opportunities to offshore energy and food production, while providing jobs for those conducting the activities, double as a benefit for those enjoying the recreational and more importantly educational opportunities these ventures offer. Through effective communication of how these operations work, the benefits and drawbacks, and seeing tangibly how they function, consumers and society at large have a chance to better understand and see first hand how these offshore processes actually operate and their relation to ecology and society.

The expansion of multi-use, particularly offshore, presents a landscape filled with challenges and opportunities. While the short-term implementation of such projects seems unlikely due to various constraints, the theoretical potential and the promise of economic and ecological benefits indicate that offshore multi-use could play a significant role in the future of sustainable food and energy production in the region. Furthermore, as discussed in Deliverables 3.1 and 3.3, the long term commitment and structural funding via grants of subsidies for such offshore activities and either mandates or clear directives to include activities is growing across Europe and is a key

² https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters_en



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point in a number of European National and EU discussion points for uptake. Using the developments realised through the UNITED project, future projects and scaled developments will enhance and scale for roll-out such solutions to begin scaled production in European waters and integration of multiple sectors through a multi-use approach.

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