Offshore Low-trophic Aquaculture in Multi-Use Scenario Realisation

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Executive Summary
This deliverable provides economic data on Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for low-trophic aquaculture (LTA) operations across the three OLAMUR pilot sites. The dataset documents the financial requirements for establishing and operating pilot LTA farms in offshore wind farm environments (Pilots A and B) and

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integrated multi-trophic aquaculture configurations (Pilot C), representing diverse conditions across the North Sea and Baltic Sea.

The CAPEX data encompasses initial investments including cultivation infrastructure (longlines, shellfish towers, mooring systems, anchoring equipment), deployment equipment, monitoring systems, and regulatory compliance costs. OPEX data covers recurring operational costs including labour, vessel operations, fuel consumption, maintenance and repairs, insurance, utilities, permits, and logistics for both deployment and harvest operations.

The economic data depicts variations in cost structures across the three pilot sites, reflecting differences in environmental exposure, distance from shore, regulatory frameworks, and operational complexity. Pilot A (Germany/North Sea) represents the highest cost scenario due to extreme offshore exposure requiring advanced engineering solutions and intensive vessel operations. Pilot B (Denmark/Baltic Sea) demonstrates moderate costs with offshore deployment complexity balanced by lower salinity adaptations. Pilot C (Estonia/Baltic Sea) shows the most cost-efficient operations due to sheltered nearshore location and synergies with existing fish farm infrastructure.

These datasets provide critical inputs for WP6 sustainability assessments, enabling comprehensive techno-economic analysis (TEA), life cycle cost assessment, and evaluation of economic viability across different multi-use scenarios. The data supports development of business models, identification of cost reduction opportunities through shared infrastructure and logistics, and assessment of economic carrying capacity for offshore LTA in European waters.

Data Access: All economic datasets have been delivered through the OLAMUR data management system (WP5) following FAIR principles, with detailed documentation of cost categories, assumptions, and calculation methodologies to ensure transparency and usability by consortium partners and future stakeholders.

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1. Introduction

This deliverable confirms CAPEX and OPEX data for LTA operations at the three OLAMUR pilot sites have been collected, validated, and uploaded to the OLAMUR data management system. The economic datasets document capital investment requirements and operational costs associated with establishing and operating pilot offshore LTA farms in multi-use scenarios.

Data collection followed standardized accounting frameworks in coordination between WP1, WP6, and WP7, ensuring consistency across sites while accommodating site-specific cost structures and regulatory requirements. The datasets provide empirical evidence for techno-economic analyses, enabling assessment of economic viability, identification of cost reduction pathways, and development of financially sustainable business models for offshore LTA.

The three pilot sites represent contrasting economic scenarios reflecting their different environmental and operational characteristics. Pilot A at Meerwind Süd/Ost offshore wind farm demonstrates high-cost offshore operations in exposed North Sea conditions. Pilot B at Kriegers Flak offshore wind farm presents moderate costs for Baltic offshore cultivation. Pilot C in Tagalaht Bay represents cost-efficient nearshore IMTA operations with infrastructure and logistics synergies.

The economic data encompasses cost categories:

- **CAPEX:** Infrastructure (longlines, mooring systems, anchors, buoys), cultivation equipment (shellfish towers, monitoring systems), deployment vessels and equipment, regulatory compliance (permits, environmental assessments), and initial seed/spat material
- **OPEX:** Labour costs, vessel operations and fuel, maintenance and repairs, insurance, utilities, ongoing permits and licenses, transportation and logistics, and operational monitoring

All costs are documented in Euros with transparent assumptions regarding depreciation periods, utilization rates, and allocation methodologies. Where partners use different accounting approaches (e.g., AWI's institutional structures versus commercial operators like Wyk 8 and Kerteminde Seafarm), both perspectives are documented to provide coast clarity

2. Economic Data by Pilot Site

2.1. Pilot A (Germany/North Sea) - Meerwind Süd/Ost

Lead Partner: AWI | Contributors: W8F, HEREON

Pilot A represents the most capital-intensive LTA deployment in the project due to extreme offshore exposure, significant distance from shore (12.4 nautical miles from Helgoland), and challenging North Sea environmental conditions requiring advanced engineering solutions.

<u>CAPEX Overview</u>

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Total CAPEX for Pilot A reflects substantial investment in robust offshore infrastructure engineered through iterative OrcaFlex modeling and wave flume testing. Major capital cost categories include:

- **Advanced mooring systems:** Newly developed SSFT (SmartFarm/Shellfish Tower) mooring system designed for extreme offshore exposure (€70,000)
- **Cultivation infrastructure:** SmartFarm longline systems and experimental Shellfish Tower units (€60,300)
- **Anchoring and mooring equipment:** Heavy-duty chains, shackles, marker buoys adapted for North Sea conditions (€45,692)
- **Monitoring and control systems:** Wave riders, GPS trackers, safety markers for the research area (€65,200)
- **Engineering services:** Professional calculation and simulation services for offshore structural analysis (€22,000)
- **Initial biological material:** Juvenile European oysters, PCR testing for parasites, seaweed seed material (€2,300)
- **Support equipment:** Water systems, aeration equipment, specialized baskets and nets (€2,950)

The high CAPEX reflects investment in technology advancement from TRL5 to TRL7, with significant engineering required to ensure system survival in one of Europe's most challenging marine environments.

<u>OPEX Overview</u>

Annual operational costs for Pilot A are dominated by vessel operations and specialized labour requirements for offshore access:

- **Labour costs:** €446,844 annually for five employees plus one additional person, reflecting specialized offshore aquaculture expertise and safety training requirements
- **Vessel operations:** Substantial costs for specialized crew transfer vessels, including charter fees, fuel, and safety equipment. Transportation and logistics total €115,680 annually, with vessel operations accounting for the majority
- **Maintenance and repairs:** €222,936 annually (estimated based on offshore operational experience and expected equipment wear in harsh conditions)
- **Insurance and regulatory:** €337,352 annually covering comprehensive offshore liability insurance, business insurance, vessel coverage, and ongoing regulatory compliance
- **Consumables and utilities:** €1,400 annually for operational supplies including fingerlings, testing, seeded lines, nets, and baskets

Vessel fuel costs ("bunker") are integrated into the transportation and logistics category, reflecting the reality that offshore access is the primary operational cost driver. The cost structure emphasizes that offshore LTA viability depends critically on identifying opportunities for shared vessel operations with wind farm operators and developing remote monitoring capabilities to reduce site visit frequency.

AWI notes specific challenges in cost allocation due to institutional research infrastructure. Where institutional assets (vessels, facilities) provide in-kind support, estimated equivalent commercial costs are documented to enable fair comparison with commercial operators. The

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Wyk 8 partnership provides commercial operational cost benchmarks reflecting realistic industry wage structures and operational procedures.

Cost Drivers and Optimization Opportunities

The Pilot A economic data identifies several critical factors affecting offshore LTA viability:

1. **Distance from shore:** 12.4 nm transit distance significantly increases vessel time and fuel costs per site visit
2. **Weather windows:** Limited operational access due to North Sea conditions requires careful seasonal planning
3. **Infrastructure robustness:** Higher initial CAPEX for robust systems reduces long-term maintenance costs and catastrophic loss risk
4. **Shared logistics potential:** Multi-use arrangements with WindMW could substantially reduce OPEX through coordinated vessel operations
5. **Remote monitoring:** Investment in autonomous monitoring systems could significantly reduce vessel visit frequency

2.2. Pilot B (Denmark/Baltic Sea) - Kriegers Flak

Lead Partner: AU | Contributors: VF, KS, KC, DTU

Pilot B demonstrates moderate cost structures reflecting offshore deployment complexity balanced by more benign Baltic conditions and shorter distance from shore (8 nautical miles from Klintholm Havn).

CAPEX Overview

Total CAPEX for Pilot B reflects investment in proven longline technology adapted for Baltic offshore conditions:

- **Mooring and anchoring:** Concrete block anchors (5 blocks × 3 tons), headlines, anchor lines, and mooring hardware (€8,154)
- **Main cultivation lines:** Four 200m mainlines with associated rigging and connection equipment (€3,669)
- **Cardinal buoys:** Corner marker system rental for two-year period (€586,667) — this represents the largest CAPEX component, reflecting stringent Danish maritime safety requirements for offshore installations
- **Buoyancy system:** Buoyancy floats for both seaweed and mussel lines (€3,000 combined)
- **Substrate and collectors:** Seeded lines for sugar kelp, standard spat collectors for mussels, connection binders (€4,658)
- **Deployment operations:** Specialized vessels for system deployment, corner buoy installation, and line establishment (€45,137)

The cardinal buoy rental cost reflects Danish regulatory requirements for clearly marked offshore installations. While this appears as a high CAPEX item, it ensures navigational safety and regulatory compliance. Future commercial operations might explore ownership models or shared marking systems within wind farm areas to reduce this cost component.

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OPEX Overview

Annual operational costs for Pilot B reflect a more accessible offshore site with structured operational seasons:

- **Labour costs:** €2,835 annually for operational personnel (substantially lower than Pilot A due to shorter operational seasons and less specialized offshore requirements)
- **Vessel operations for deployment/harvest:** €4,000 annually (two days per year at €2,000/day) for seaweed deployment and mussel line establishment plus harvest operations
- **Vessel operations for monitoring:** Two operational scenarios documented:
    - **Without multi-use coordination:** €8,000 annually (eight monitoring days at €1,000/day vessel cost)
    - **With multi-use coordination:** €2,000 annually (two monitoring days at €1,000/day vessel cost) — representing 75% cost reduction through shared operations with Vattenfall wind farm
- **Fuel costs:** €267-401 annually depending on operational intensity (based on 50L/day at DKK 5/L)
- **Personnel for vessel operations:** €5,120-7,680 annually (two persons, 8-hour days at DKK 320/person/hour)
- **Maintenance and repairs:** €32,613 annually (estimated at approximately 5% of CAPEX for routine rope replacement, buoy maintenance, and minor gear repairs)
- **Utilities:** €300 annually for shore-side electricity and water use
- **Permits and licenses:** Covered through AU institutional arrangements; commercial operations would incur licensing costs

The multi-use scenario demonstrates substantial OPEX reduction potential. Coordination with Vattenfall for combined site visits could reduce annual monitoring vessel costs by €6,000 (75% reduction), significantly improving economic viability. This provides strong evidence for the value of multi-use governance frameworks enabling shared operational logistics.

Cost Drivers and Optimization Opportunities

The Pilot B economic data highlights several factors affecting Baltic offshore LTA economics:

1. **Regulatory marking requirements:** Cardinal buoy costs represent major CAPEX component; future installations should explore optimized marking strategies
2. **Multi-use coordination value:** Reduction in monitoring costs through shared vessel operations demonstrates clear economic benefit of multi-use arrangements
3. **Seasonal operation:** Clear seasonal windows for deployment and harvest enable efficient labour utilization
4. **Moderate accessibility:** 8 nm distance provides reasonable balance between offshore benefits and operational access
5. **Established supply chains:** Proximity to existing aquaculture infrastructure (Kerteminde Seafarm) reduces logistics complexity and costs

2.3. Pilot C (Estonia/Baltic Sea) - Tagalaht Bay IMTA

Lead Partner: UT | Contributors: RS, ÖA

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Pilot C represents the most cost-efficient operational scenario due to sheltered nearshore location, synergies with existing fish farm infrastructure, and simple IMTA configuration.

CAPEX Overview

Total CAPEX (€103,448) for Pilot C reflects straightforward nearshore deployment:

- **Mooring and anchoring:** Metal anchors (500 kg), headlines, and anchor lines (€20,720)
- **Buoyancy system:** Corner buoys, compensation floats, and surface markers (€23,400)
- **Cultivation lines:** Substrate (dropper) ropes for mussel cultivation and *Ulva* attachment (€36,600)
- **Rigging and connections:** Service ropes, tying lines, compensation weights and connections (€22,728)

The relatively modest CAPEX reflects proven longline technology deployed in sheltered conditions without extreme offshore engineering requirements. The IMTA configuration leverages existing fish farm infrastructure for access and logistics, eliminating standalone shore facility costs.

OPEX Overview

Annual operational costs for Pilot C demonstrate cost-efficient nearshore operations:

- **Labour costs:** €2,835 annually for operational management and harvest operations
- **Maintenance and repairs:** €5,000 annually (approximately 5% of CAPEX for routine replacement of ropes, buoys, and minor gear repairs)
- **Laboratory supplies:** €600 annually for water quality sampling and product testing
- **Transportation and logistics:** €1,992 annually combining:
  - Farm-to-processor logistics (€1,500 annually for truck hire and handling)
  - Vessel fuel (€492 annually based on OLAMUR data: 4.1 kg diesel/ton biomass × 63 tons yield = 258 kg diesel ≈ 307 L @ €1.60/L)
- **Utilities:** €300 annually for electricity and water (shore-side support from fish farm facilities)
- **Insurance:** €800 annually for basic vessel and farm liability coverage
- **Permits and licenses:** €2,000 annually for Estonian aquaculture licensing

Total annual OPEX approximately €13,527, representing dramatically lower operational costs compared to offshore pilots. The cost efficiency stems from sheltered location minimizing vessel requirements, proximity to shore enabling low-cost logistics, and integration with existing fish farm operations providing infrastructure and utilities support.

Cost Drivers and IMTA Economic Advantages

The Pilot C economic data demonstrates several factors contributing to cost-efficient LTA operations:

1. **Sheltered location:** Protected conditions enable simpler infrastructure and eliminate extreme weather operational constraints

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2. **Infrastructure sharing:** Integration with RedStorm fish farm provides vessel access, shore facilities, utilities, and staff support
3. **Short distance:** Port distance enables rapid, low-cost site access with small vessels
4. **Regulatory efficiency:** Estonian licensing framework provides clear pathway for IMTA operations
5. **Nutrient subsidy value:** Proximity to fish farm potentially enhances LTA growth rates, improving production per unit investment (ecosystem service value addressed in WP3)

3. Cross-Site Economic Analysis

The CAPEX and OPEX datasets across all three pilot sites reveal patterns in offshore LTA economics:

Cost Structure Patterns

Distance from shore emerges as a primary cost driver. Pilot A (12.4 nm) shows vessel operation costs dominating OPEX, Pilot B (8 nm) demonstrates moderate vessel costs with significant multi-use savings potential, while Pilot C (< 2 nm) achieves minimal vessel-related costs. This gradient provides validation for site selection economic models in WP2.

Environmental exposure directly impacts CAPEX through infrastructure requirements. Pilot A's extreme North Sea exposure necessitates advanced engineering (SSFT mooring system, wave-tested longlines) driving high capital costs, while Pilot C's sheltered conditions enable proven technology at fraction of the cost. This relationship informs WP6 economic viability assessments across different offshore site classifications.

Multi-use arrangements demonstrate quantifiable economic value. Pilot B documents reduction in monitoring costs through coordination with Vattenfall, providing empirical evidence for WP7 governance recommendations regarding shared operational frameworks. The potential OPEX savings justify investment in multi-use coordination mechanisms.

Regulatory frameworks significantly affect cost structures. Danish cardinal buoy requirements drive major CAPEX component at Pilot B, German offshore regulations influence insurance and safety costs at Pilot A, while Estonian IMTA licensing provides relatively streamlined pathway at Pilot C. This variation informs WP7 governance analyses of regulatory barriers and harmonization opportunities.

Economic Viability Implications

The datasets enable assessment of production costs per ton biomass once harvest data is complete. Preliminary analysis suggests:

- Offshore locations (Pilots A and B) require higher biomass yields or premium product values to achieve economic viability
- IMTA configurations (Pilot C) benefit from lower costs and potential ecosystem service value, improving economic margins
- Multi-use coordination provides significant OPEX reduction pathway critical for offshore viability

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These findings will support WP6 development of business models and identification of market opportunities that can support offshore LTA investment.

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4. Data Quality and Methodology

All economic data have been validated through multiple approaches:

- **Direct operational records:** Actual expenditures from pilot operations where available
- **Commercial benchmarks:** Industry partner data (Wyk 8, Kerteminde Seafarm) providing realistic cost structures
- **Engineering estimates:** Professional calculations for specialized equipment and deployment operations
- **Institutional cost equivalents:** Where research infrastructure provides in-kind support, equivalent commercial costs estimated for transparency

The economic datasets acknowledge limitations including:

- Pilot scale operations will almost certainly not reflect commercial economies of scale
- First-year deployment costs include learning curve inefficiencies
- Insurance costs vary widely based on operator risk profiles and available coverage
- Some institutional costs are estimated rather than directly measured

These limitations are documented to ensure appropriate interpretation by WP6 economic analyses.

5. Data Integration and Conclusions

The CAPEX and OPEX datasets from all three pilot sites provide an empirical foundation for economic assessment of offshore LTA across diverse operational scenarios. The data demonstrate:

1. **Cost variation:** OPEX ranges from ~€13,500 annually (Pilot C) to >€800,000 annually (Pilot A), driven primarily by environmental exposure and distance from shore
2. **Multi-use economic value:** Documented OPEX reduction through coordination with wind farm operations provides quantitative evidence for governance frameworks enabling shared logistics
3. **IMTA cost efficiency:** Integration with existing aquaculture operations reduces both CAPEX and OPEX, supporting IMTA as economically advantageous model
4. **Offshore viability challenges:** High costs in exposed offshore environments require either very high production yields, premium product values, or significant shared infrastructure benefits to achieve commercial viability

All datasets have been uploaded to the OLAMUR data management system (WP5) following FAIR principles with comprehensive metadata, assumptions documentation, and quality flags. The economic data are being utilized by:

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- **WP6:** Techno-economic analysis, business model development, life cycle cost assessment
- **WP2:** Site selection economic feasibility assessments and cost-benefit analysis for MSP
- **WP7:** Governance framework evaluation including regulatory cost impacts and multi-use coordination value
- **WP8:** Stakeholder communication regarding economic viability and investment requirements

Future work will integrate production yield data from D1.3 enabling calculation of production costs per unit biomass, revenue potential assessments, and comprehensive economic viability analysis across the different offshore LTA scenarios represented in OLAMUR pilot operations.

6. Acknowledgments

The economic data collection benefited from contributions by commercial partners Wyk 8, Nordfriesische Seemuschel GmbH, Kerteminde Seafarm, RedStorm OÜ, and Ösel Aquafarms OÜ, who provided cost structures from commercial aquaculture operations. Wind farm operators WindMW and Vattenfall provided infrastructure insights on multi-use coordination opportunities. All pilot site teams contributed systematic operational cost tracking throughout deployment and cultivation phases.

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