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Deliverable: D 6.3 Synergies of Multi-Use Platform (MUP)

Work Package 6: Transport and Optimization of Installation, Operation and Maintenance

Task 6.3 The synergies and disadvantages of MUP

Deliverable: D 6.3 Synergies of Multi-Use Platform (MUP)	
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ABBREVIATIONS

DNV	:	Det Norske Veritas
DP	:	Dynamic Positioning
GW	:	Giga Watt
Hs	:	Significant wave height
MERMAID	:	Multi-purpose off-shore platforms: planning, design and operation
MCA	:	Maritime and Coastguard Agency
MUP	:	Multi-Use Platforms
MW	:	Mega Watt
nmi	:	Nautical Miles
NWI	:	NorWind Installer
OWF	:	Offshore Wind Farm
OWT	:	Offshore Wind Turbine
O&M	:	Operation and Maintenance
WEC	:	Wave Energy Converters
WFSV	:	Wind Farm Service Vessel

Summary

Ever increasing marine construction and human activities in the European seas necessitates more judicious planning in the use of ocean space. An offshore wind farm (OWF) occupies a large area and this might be in competition with fishing or other activities in the region. Co-use of ocean space, with aquaculture inside a wind farm, might offer a possible means to mitigate some of the negative effects of reserving large areas for wind farms alone. This report D6.3 follows the deliverable report 6.2: the Multi-Use Platform (MUP) case. Deliverable 6.2 gave a basic illustration of a MUP involving energy extraction and aquaculture in the same farm for co-use of ocean space; whereas deliverable 6.3 is focused on the synergies and disadvantages of the MUP with regard to the yield, cost and risks during installation and operation, and impacts on the marine environmental during the construction and operation phases.

This deliverable 6.3 presents the case study of innovative MUPs: the analysis of aquaculture farming within offshore wind farms. The case study focuses on four aspects. First, this study proposes the combined fish, mussels and seaweed production systems for two types of 1000 MW wind farms at two water depths. Second, the study introduces efficient installation methods for 10 MW wind turbine generator (WTG) (one with a jacket foundation and one with a floating structure). The third aspect concerns the installation of the large fish cages, mussels and seaweed production systems. The final aspect addresses the synergies and risks of combining various deployments and operations of an MUP. Ultimately this MUP case study demonstrates the promise of ocean space co-use. It also beckons the technology development of the aquaculture farming under harsh offshore conditions.

Firstly, the large area contained within the proposed wind farm has the potential to create a high revenue aquaculture production, including salmon/Sea Bass, mussel and seaweed. The 1000MW study cases show that the potential to create annual salmon production of 60,000 to 70,000tons (yield of 240 to 280M€ at €4/kg) and sea bass 90,000 to 105,000tons (yield of 360 to 420M€ at 4€/kg) at the North Sea and Atlantic site, respectively. This yield, in financial terms, would account for 50 – 60% and 76 - 89% of the annual electricity yield respectively.

Secondly, a more efficient installation method of a10MW WTG and an aquaculture system are proposed. A numerical model of lowering and landing a 10 MW offshore wind turbine (OWT) jacket foundation by a floating installation vessel was established in order to check vessel workability.

Thirdly, the installations of the large fish cages, mussels and seaweed production systems have been addressed. The fish cages for the aquaculture farming usually have a much smaller weight compared to the component of the OWF. The installation of a group of eight fish cages (circular: circumference 120 m, depth 25 m) is assumed to take a one-month offshore work duration. The fish cages will be assembled onshore and towed complete to the offshore site.

Fourthly, there are also many risks from the MUP approach. There are at least three major risks related to the implementation of conventional large fish cages within the offshore wind farm:

i) Most conventional fish cages and their mooring systems have been designed for operation at inshore protected sites. Unfortunately, these fish cages and mooring systems might be damaged under the harsh conditions of offshore wind farm sites.

ii) The fish cages with their mooring systems placed within the OWF might increase collision risks with the operation, service and large maintenance vessels. This is possible despite the large space between the wind turbines.

iii) There are conflicts between the offshore wind and aquaculture farms during the installation and operation phases.

Many more risks resulting from the MUP should be identified during the installation and O&M phases. Problems related to the licensing, policy, insurance costs, and the sharing among the different stakeholders might appear. The ecological impacts related to an MUP are briefly mentioned in this deliverable and the further study belongs to the work scope of WP4 in this project.

1 Introduction

1.1 Motivation and background

Ever increasing marine construction and human activities in the European seas necessitate more judicious planning in the use of ocean space. This planning must consider the multi-use of ocean space to minimize environmental impacts. Within this concept, the EU-FP7-funded research project "Innovative Multi-purpose Off-shore Platforms: Planning, Design and Operation (MERMAID)" aims to integrate marine energy extraction and aquaculture activities in MUPs [1]. However, there are many bottlenecks related to the various deployments and operations of Multi-Use Platforms (MUPs). Accordingly, work package 6 in MERMAID explores innovative transport technologies and the goal of deliverable D6.2 [2] is to address the technology challenges of potential MUP installation, operation and maintenance (O&M), through proposed solutions.

This deliverable D6.3 presents the synergies and the disadvantages of the MUP compared to an OWF. The most crucial installation processes, e.g. installation of large Wind Turbine Generator (WTG), will be assessed by numerical simulations to evaluate the feasibility of new proposed installation technologies.

1.2 Study Objectives

The MUP case study described here is located at the North Sea site and the floating WTG installation at the Atlantic sea site. The 100 units of future large-scale 10MW WTGs, with both fixed foundation and floating concept, will be discussed. The specific transport technologies for installation, O&M of both the wind farms and aquaculture farms will be proposed. The installation of the wind farm with monopile foundation will refer to the experience of Statoil's Sheringham Shoal OWF of 318MW, in the UK. The transport technologies proposed for the wind farm with floating WTGs will be based on the Hywind experiences [5].

The four goals of the proposed MUP case study are listed as follows.

- Proposes the combined fish, mussels and seaweed production systems for two types of 1000 MW wind farms at two water depths.
- Introduce efficient installation methods for 10 MW wind turbine generator (WTG) (one with a jacket foundation and one with a floating structure).
- The installation of the large fish cages, mussels and seaweed production systems.
- Address the synergies and risks of combining various deployments and operations of an MUP.

2 MUP Case Study

2.1 MUP layout at the North Sea Site

The selection of the site was not project-specific and it is located in the southern North Sea at 40m water depth and 100km from the coast line. This specification for the study case was chosen in order to describe more challenges for the transportation and installation solutions.

The base case of the proposed 1000MW wind farm is shown in Fig. 2.1, with 100 fixed foundation 10MW WTG units and two offshore substations. Note the 10MW WTG is not yet commercially available and the estimation of 10MW WTG is used for installation and operation evaluation. It is assumed that the required distance between WTGs is 1600m downwind, in the prevailing wind direction and 1200m in other directions.

The layout of the 1000MW considers the electrical grid array, wake effects and the installation, O&M phases. This signifies that the wind farm occupies an area of 138km^2 and a total of 72 large areas are contained within the OWF zone, which have the potential to yield high value aquaculture products. Minimum distance between the aquaculture farming facilities and the foundation of the offshore wind foundation is assumed to be at least 500m.

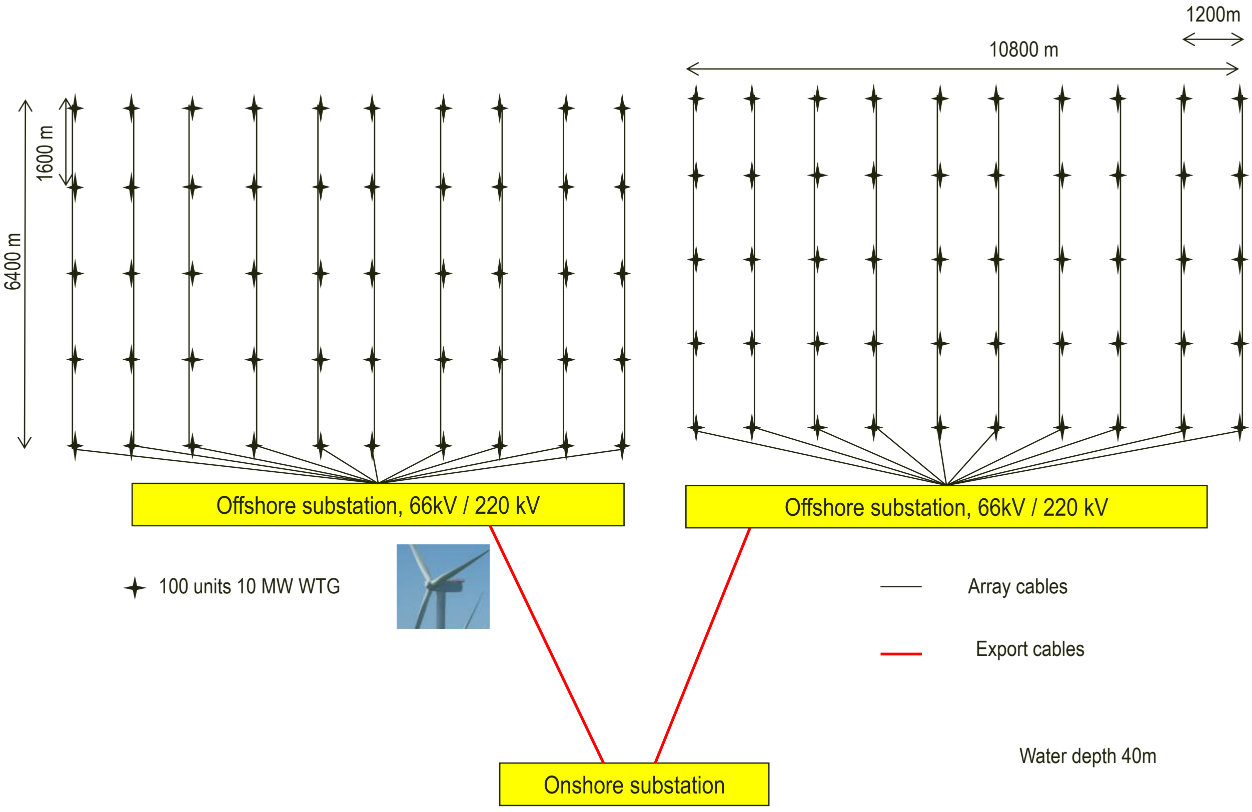

Figure 2.1 Layout of a 1000MW (100 units of 10MW) wind farm (North Sea case study)

Figure 2.2 is a proposal for a combined mussel, seaweed and salmon production within the 1000MW OWF. For Atlantic salmon and trout, 16 units of 8 circular fish cages (circumference 120m, depth 25m) will be used. There are eight mussel and 18 seaweed culture systems. Seaweed production has the ability to attenuate waves and the potential to absorb fish dissolved wastes (if growth cycles are timed correctly) to reach sustainable levels. The production rates and yields of the 1000MW wind farm with aquaculture farming inside (Fig. 2.2) are given in Table 2.1.

The electricity annual production is estimated to be 3300GW/h, at an annual average wind speed of 9.5m/s, based on the 10MW WTG power production characteristic. The annual salmon production is 60,000 to 70,000 tons based on the fish production rate: 20 kg/m3 (maximum rate: 25 kg/m^3) and the fish survive rate: 88% to 95%. This yield, in financial terms, would be yield of 240 to 280 M€ at €4/kg, which accounts for 50 to 60% of the annual electricity yield. In addition, the productions from the blue mussels and seaweed (e.g. sugar kelp) are 20,000 to 30,000 tons and 160,000 to 180,000 tons respectively. The yields from Blue mussels and seaweed are estimated to be 20 to 30 M€ and 160 to 210 M€ respectively (at €1/kg for both mussels and seaweed).

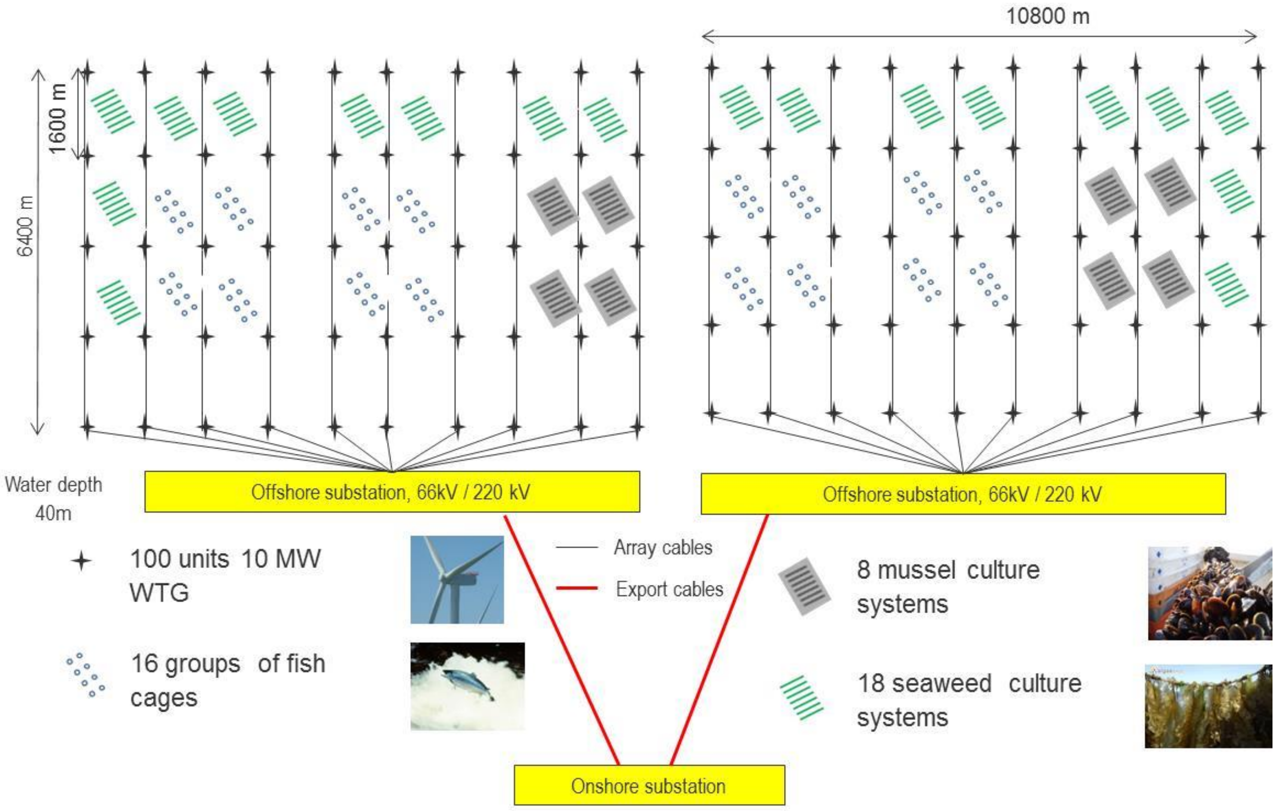

Figure 2.2 Layout of 100 units of 10MW floating offshore wind turbine generators with aquaculture farms.

This scenario presents a promising co-use of ocean space by the wind power generation industry and salmon, mussels and seaweed production. The productions and yields presented in Table 2.1 demonstrate that aquaculture farming has the potential to improve offshore wind economics.

Table 2.1 Estimates of the MUP annual potential production rates and yields

	Annual production	**Annual yield**	**Comments**
Electricity	3300GW/h (annual average wind speed 9.5m/s)	471 M€ (0.14 € /kWh^{-1})	
Salmon production	60 - 70 000 tons	240 to 280 M€ (4 € /kg)	Amounts to 50 - 60% of the electricity yield!
Blue mussels	20 - 30 000 tons	20-30 M€ (1 € /kg)	
Seaweed (e.g. sugar kelp)	160 - 180 000 tons	160-210 MEUR (1 EUR/kg)	Attenuates waves and absorbs fish wastes

2.2 MUP layout at the Atlantic Sea Site

In this MUP case study, Hywind will be used. A field layout for 100 units of 10MW offshore WTGs in combination with facilities for fish farming, mussel and seaweed culture systems can be seen in Fig 2.3.

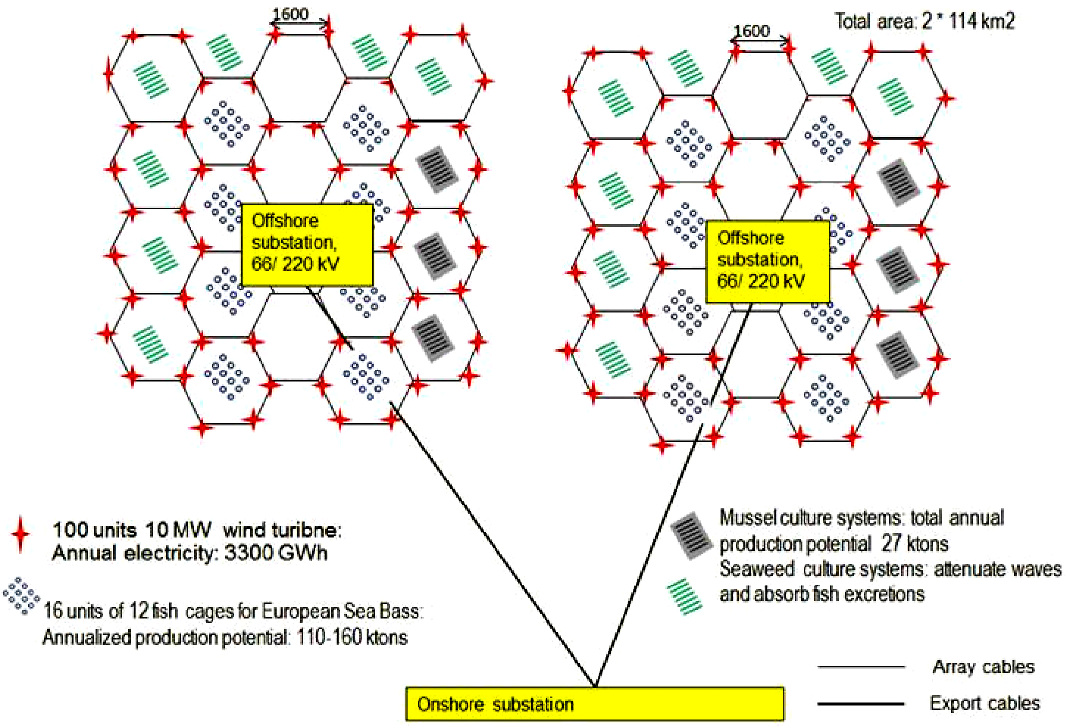

Figure 2.3 Layout of 100 units of 10MW floating offshore wind turbine generators with aquaculture farms.

The estimation of the production rates and yields of the 1000MW wind farm integration with aquaculture (as shown in Fig. 2.3) is given in Table 2.2. There are 16 units of 12 circular fish cages with circumference 120m and depth 25m. It is noted that the European sea bass production amounts to 76-89% of the electricity yield. There are six and 14 groups for mussel and seaweed culture systems respectively. The seaweed production has the potential to attenuate waves and to absorb fish dissolved wastes (if growth cycles are timed correctly) to reach sustainable levels.

Table 2.2 The MUP potential annual production rates and yields.

	Annual production	Annual yield	Comments
Electricity	3300 GW/h	471 M€ (0.14 € /kWh)	
European sea bass	90-105 000 tons	360 to 420 M€ (4 € /kg)	Amounts to 76-89% of the electricity yield!
Blue mussels	23-34 000 tons	23-34 M€ (1 € /kg)	
Seaweed (e.g. sugar kelp)	250-290 000 tons	250-290 M€ (1 € /kg)	

2.3 Components of the 1000MW Wind Farm to be installed

The dimension of the 10 MW WTG is illustrated in Figure 2.4. The technical and operational solutions for the transport and installation of foundations, WTGs, cables and substation for a 1000MW OWF will be proposed. The dimensions, weight of the four types of components and the installation refer to Deliverable 6.2.

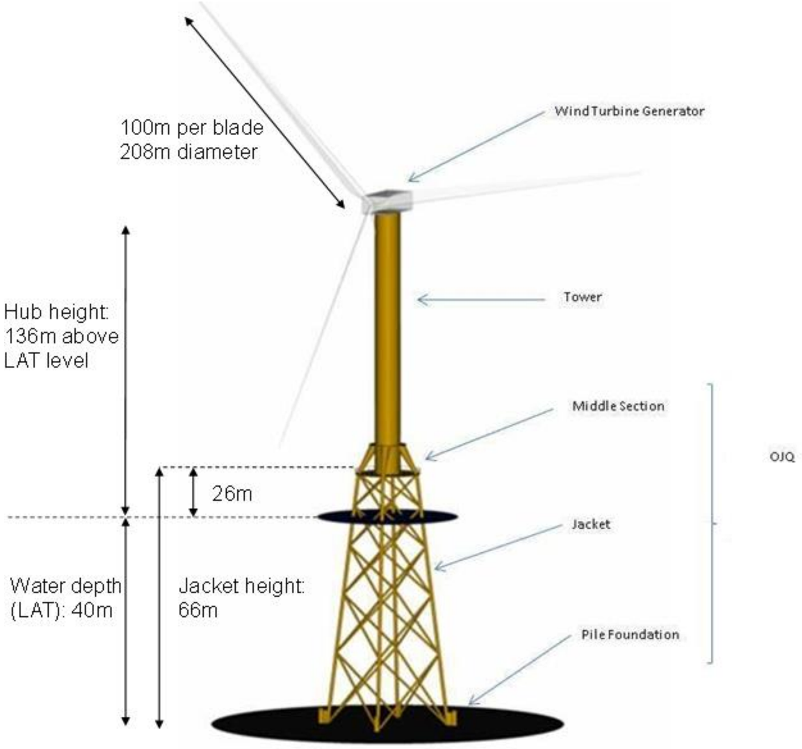

Figure 2.4 Example of a 10 MW WTG with a jacket at 40m water depth is used in the study case.

2.4 Numerical model of the installation process of the jacket foundation

In this study, a numerical model of lowering and landing a 10 MW offshore wind turbine jacket foundation by a floating installation vessel was established in order to check vessel workability. This section gives a brief overview of the model and the simulation results; for details on the elaborate model and simulation description refer to [8].

The numerical model includes the vessel with dynamic positioning and the 10MW jacket foundation. Due to the couplings between the two bodies during the operation, multi-body time domain simulation software is required. In this study, the software SIMO [9] was used as the numerical tool, and Fig. 2.5A shows the numerical model. Only the submerged part of the vessel is displayed in the figure. The system included two rigid bodies, i.e., the installation vessel and the jacket. The connection between the vessel and the jacket is through lifting wires assuming a hydraulic gripper was applied inside the transition piece instead of a traditional hook (Fig. 2.5B).

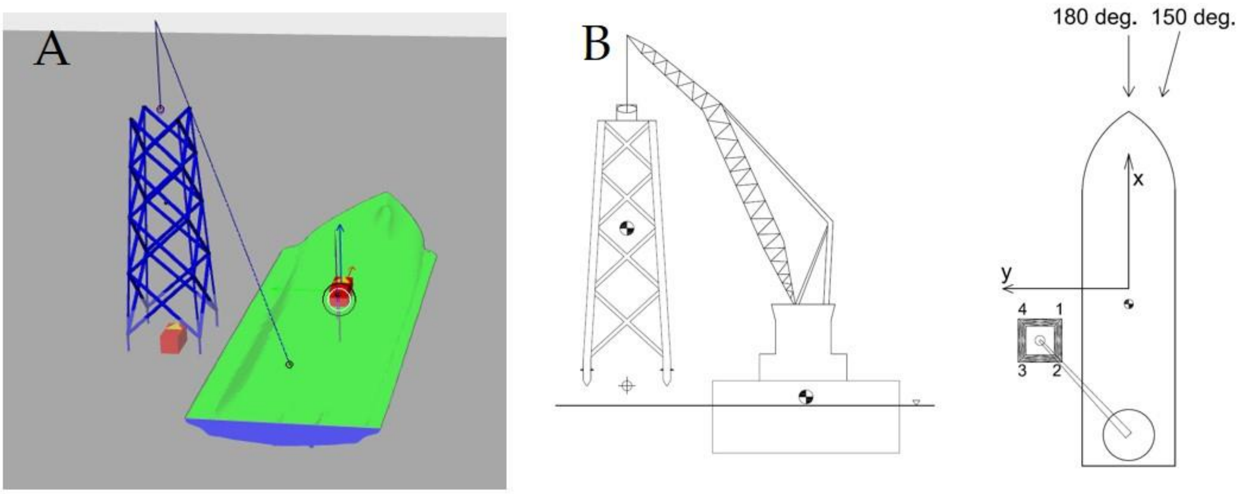

Figure 2.5 Numerical model in SIMO (A) and definitions of global coordinate system (B).

Figure 2.6 shows an example of the time history of critical responses by using the installation vessel with the dynamic position and a jack-up vessel, respectively. For the jack-up vessel case, the vessel is fixed on the sea bed during the whole lowering and landing process. The responses include the motions at the jacket lower tip, the rotations of the jacket, the lift wire tensions and the docking forces. As shown, the whole lowering process of the jacket can be divided into three phases and these are now discussed.

Phase 1: In air. The jacket is hanging in air after lift off from a transportation barge or from the installation vessel. When a jack-up vessel is used, there are no translational or rotational motions in this phase since the crane is still and no forces are acting on the jacket (wind forces were ignored). However, the pendulum motions are excited by the motions of the floating vessel. Due to little damping in air, the pendulum motion amplitudes are huge. Possible methods to reduce the pendulum motions in air, e.g, by applying tugger wires will also be studied.

Phase 2: Lowering phase. The lowering phase begins around 250 sec, when the jacket lower end enters the splash zone. In this phase, due to the wave forces acting on the jacket members, the motions are no longer zero when using the jack-up vessel. For the floating vessel case, with the increase of the submergence of the jacket, the drag forces, quadratic in nature, provide a lot of damping for the system and the large pendulum motions are relatively damped out from around 400 sec to 300 sec. However, with further increase in submergence, the motions increase again due to significant wave forces acting on the jacket members. This can be also observed for the jack-up case. In general, the motions are much larger from an installation vessel with dynamic positioning than using a jack-up vessel at this wave conditions since the crane tip motions are larger.

Phase 3: Landing. This phase begins when the first docking force occurs, which is when the jacket legs start to land into the pre-installed piles. A huge landing force can be observed in the time series. Due to the high-frequency landing forces, the frequencies of the jackets are much higher than in the previous two phases. Due to the restrictions from the pile diameter, the translational motions at the tip are constrained, while the rotations remain critical (the legs can still rotate in the docking cones). The landing force is important criteria for this phase and a structural analysis should be conducted to ensure structural integrity. At the end of this phase, the jacket legs stand on the fender stoppers, and the lift wire tension decreases to zero.

The critical responses are different at different phases. So the most relevant criteria should be applied for each phase to check the workability.

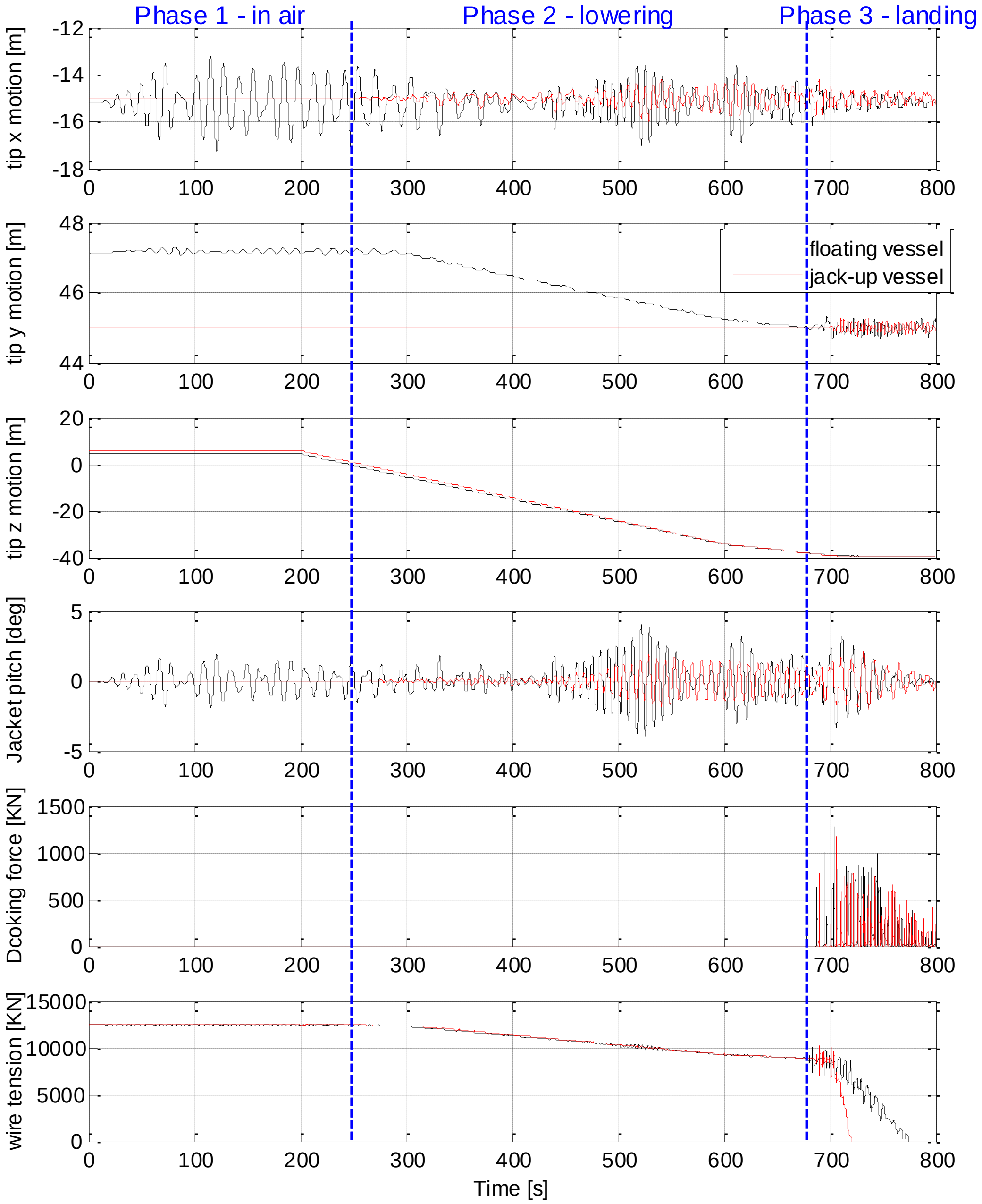

Figure 2.6 Time history of the three phases (in air, lowering and landing) of a jacket foundation installation. Conditions: Hs =2.0 m, Tp=9.0 s, Dir=180 deg, Seed = 1.

2.5 Installation of 100 units of 10 MW floating wind turbines

This section briefly discusses the technology of the floating wind turbine installation. If a vertical assembly strategy is to be used, the transport and assembly procedure will be very similar to that of Hywind Demo [4]. A sub-structure must be manufactured at a suitable yard, transported to the assembly site and up-ended. The tower sections, nacelle and rotor must be manufactured by the turbine supplier, transported to the assembly site and lifted onto the sub-structure in a number of (typically four) lifting operations (Fig. 2.7). Due to the deep draft of the sub-structure it is most likely that the lifting operations must be done using a floating crane (unless a quay with more than 120 meter depth is available). Because of the large lifting heights, the operations will then become weather sensitive. In the case of Hywind Demo, there were very strict limitations on the wave height and period (the period being the most critical), and for a 10 MW Hywind turbine, the lifting height will be even larger (136 m hub height + lifting arrangement), while the weather limitations will be even more strict. In any case one would have to use large and expensive crane vessels (e.g. S7000, Thialf, or similar). Additionally, the operations would have to take place in sheltered waters (i.e. not near the Atlantic site) and then the fully assembled turbines would have to be towed to the Atlantic site.

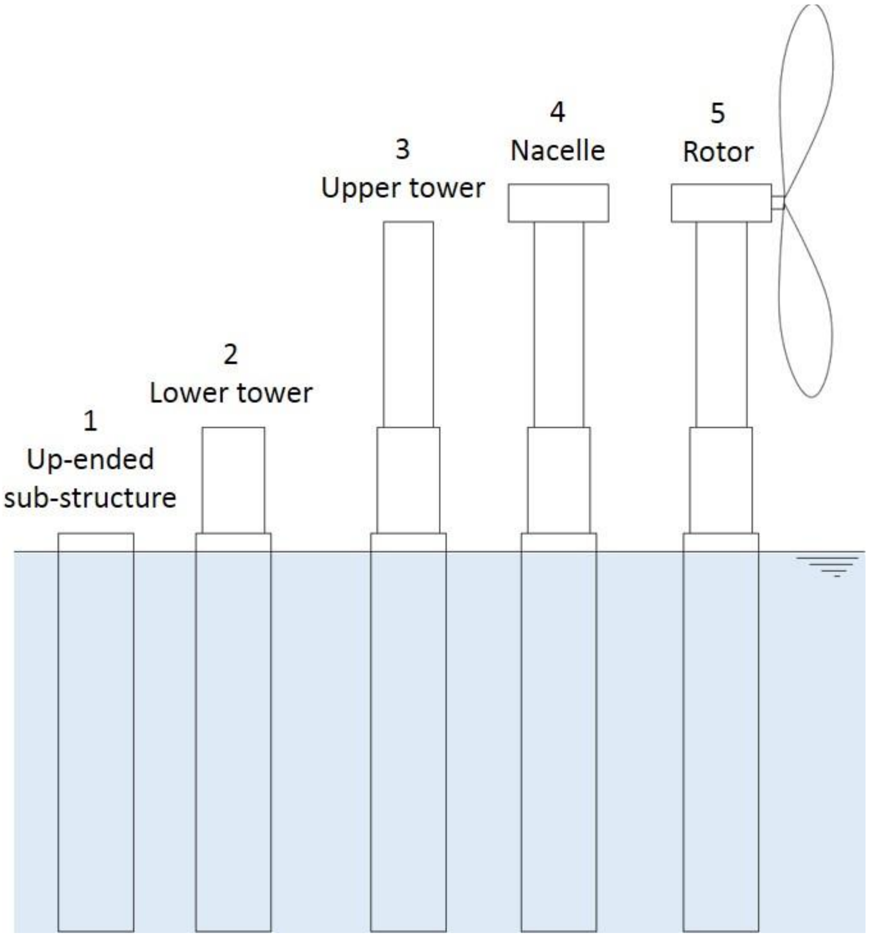

Figure 2.7 Phases of vertical assembly procedure for a three-bladed wind turbine.

2.6 Installation of an Aquaculture Farm

The fish cages for the aquaculture farming (Fig. 2.8) usually have a much smaller weight compared to the component of the OWF. The installation of a group of eight fish cages (circular: circumference 120 m, depth 25 m) is assumed to take a one-month offshore work duration. The fish cages will be assembled onshore (Fig. 2.9A) and towed complete to the offshore site. The offshore cage mooring needs a work boat with a deck area of 6 * 10 m2 and a crane lifting capacity of 6 tons. The personnel needed are between four to five crew members plus two divers. Figure 2.9B demonstrates the fish farm in operation at an offshore site and Fig. 2.9C displays the next generation of strong off-shore fish cages.

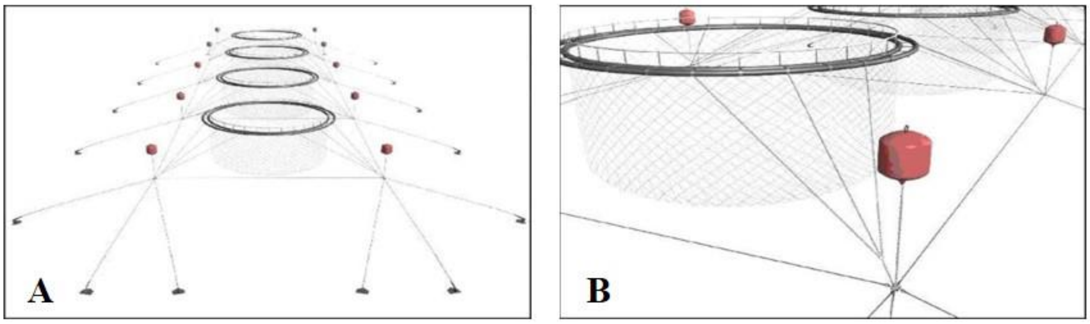

Figure 2.8 Layout of the fish cage arrangement (A), including the mooring system (B) (Courtesy Aqualine AS).

Figure 2.9 Fish cage assemble onshore (A); Fish cage operation offshore (B); and next generation strong fish cage (C).

Mussel production is assumed to use 20 m production lines (drops). Cages for this purpose can be submerged (5-7 m below mean sea level) during storms to avoid loss of mussels. The mussel production system is illustrated in Fig. 2.10.

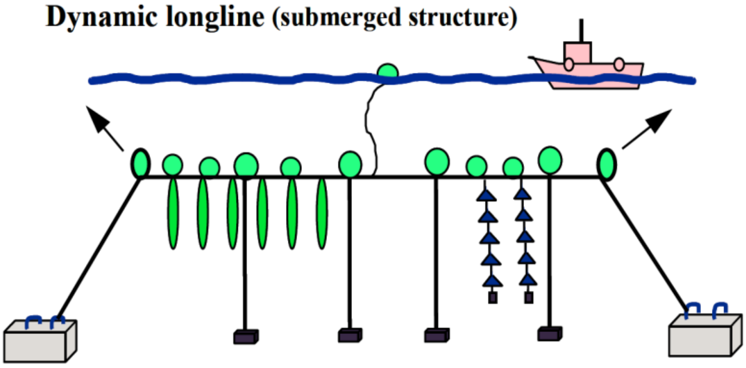

Figure 2.10 Layout of the mussel production system.

Multi-integrated aquaculture uses the waste products of one cultured species (e.g. salmon) as a valuable nutrient source for another commercial species (e.g. seaweed). The seaweed production system, besides its potential to absorb fish waste, also attenuates waves. To be successful, there must be synchronization between the growing cycles of the cultures species [12]. Also, investigations need to be performed to determine which cultivation method is most efficient for each site [11]. The installation period of a seaweed cultivation system unit (10 m width and 100 m long) with seven H structures (Fig. 2.11) takes approximately 12 hours.

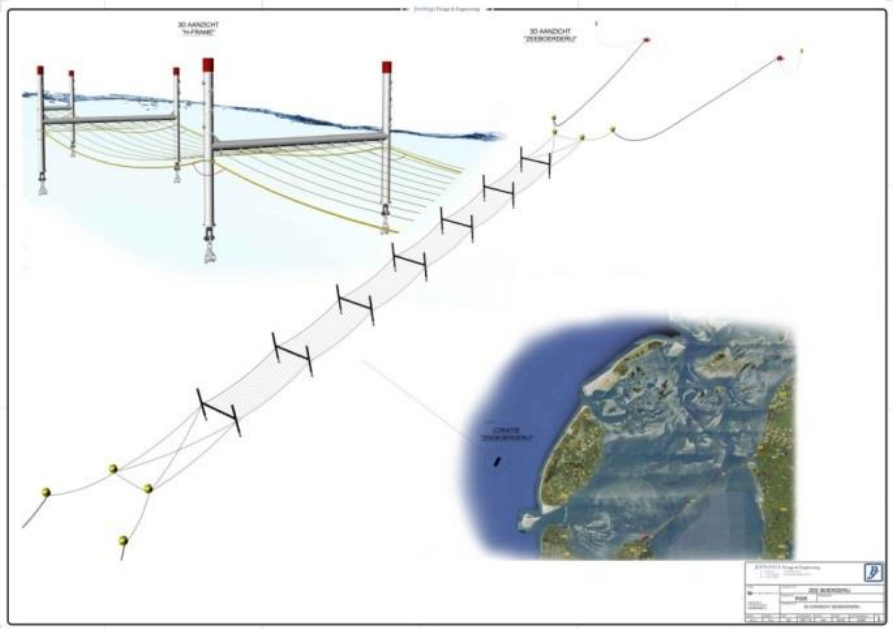

Figure 2.11 A seaweed cultivation system with H structure (Courtesy Hortimare [7])

3 Synergies and Risks during installation and operation phases for MUP's

3.1 Introduction

Offshore renewable energy production in combinations between wind- and wave energy and even tidal energy has the potential for a more efficient utilization of a possible offshore site originally optimized for one kind of energy production.

Combinations of offshore energy- with offshore food production are new and untested possibilities for both energy- and food production. However the question is how to utilise and optimize the different kind of installations/operations in combined offshore MUP´s facilities.

If an offshore wind farm (OFW) today is decided at a certain offshore site, the process for installation and operation of the wind farm will be optimized for that specific purpose in order to reduce cost of energy. Including other kind of energy production and/or food production will in many ways lead to a less optimized management of the wind farm installation and operations. Such “negative synergies” also need to be taken into account.

This report analyses possibilities for synergies and risks during installation and operation of offshore MUPs where some of the mentioned combinations are realized.

The elements where synergies might be obtained are through combined use of:

- Port and storage facilities
- Ships, shipping facilities, helicopters etc.
- Cranes
- Personnel and training of personnel
- Accommodation platforms
- Purchase of equipment
- Supervision of offshore operations
- Powering of offshore facilities
- Finance of project
- Common data essential for off-shore installations (Wind, wave, geotechnical data etc.)
- Combined installation (example Wind/Wave)

Major risks during the installation and operation phases might be:

- Mutual dependency and increased complexity due to the combination of two or more fully optimized installation activities.
- Difficulty in obtaining consent, as more stakeholders are to be taken into account due to new types on environmental issues.
- Different standards for working procedures, e.g. within Health and Safety.
- Mooring lines (risk for ships - can break etc.)

- Security and insurance cost

3.2 Cost reduction possibilities

Overall the final goal for synergies and risks are cost reductions. Therefore a good starting point will be to look at the existing distribution of cost. Here a wind farm will be a good starting point and in reference [14] is examined the cost distribution for different offshore wind parks. The Fig. 3.1 shows that the most relevant capital costs for an offshore project can be separated into the wind turbine, the cost for O&M, support structure and electrical connection. Significant cost reductions must be obtained inside these areas to impact the overall economy.

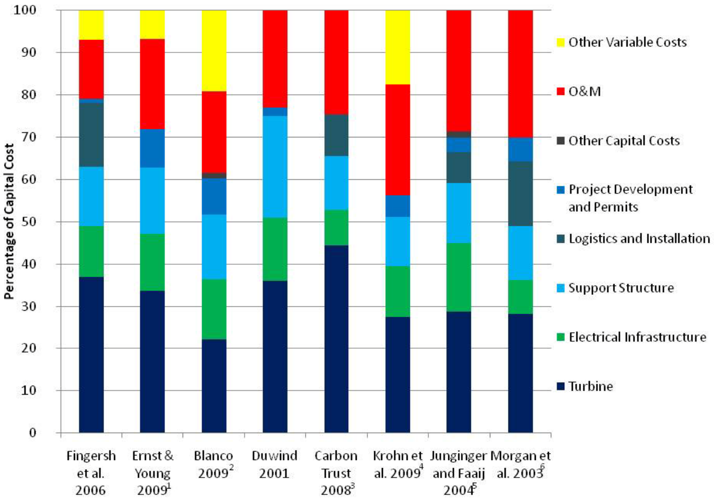

Figure 3.1 Cost distribution for offshore wind farm (from [14]).

The combination between an offshore wind farm and other offshore activity will not reduce turbine cost, but for all the other parameters like electrical infrastructure, O&M, support structure, project development and permits etc. synergy effects might be considered.

Operation and maintenance (O&M) cost typically amounts to 25-30% of the total lifecycle costs of offshore wind farms [15], and hereby represents a considerable part of the total cost for an offshore wind farm The combination of offshore wind energy and offshore aquaculture might be of interest with additional possibilities to reduce some of the installation- as well as O&M costs by synergy effects through the combined operations.

Combinations of wind farms with as example wave energy has been on the drawing table for many years and also aquaculture within offshore wind farms has been identified as a possibility for optimal use of the marine space. Aquaculture is a broad term and includes the culture of both shellfish, fin fish, and aquatic plants.

However, the aquaculture sector still has to demonstrate that this is a feasible possibility. Offshore areas for aquaculture might be exposed to high currents as well as high wave action, therefore this activity faces major challenges compared to coastal aquaculture. Ships are required to transport all inputs to and from the farm, resulting in higher operational costs than for coastal aquaculture sites. The main reasons to develop offshore aquaculture are the often favourable conditions for growth due to water depth and hydrodynamics, and less potential for spread of disease, pollution and agricultural interactions.

3.3 Installation

3.3.1 Installation of an energy producing off-shore unit

For offshore energy production mostly wind, wave and tidal energy are in question. Wind is considered to be the overall governing type of offshore energy production that in the future might be combined with offshore food production of any kind. Hence installation and O&M for wind production will have the highest priority in this chapter.

According to reference [16], the cost distribution and main components for installation of offshore wind platforms might be as follows:

Table 3.1 Cost distribution for a typical offshore installation [16]. Mean cost: 2,5-3 mill EUR/MW.

Hardware		**Installation**	
Foundation	15%	Foundations	5%
Turbines	45%	Turbines	5%
Cables	15%	Cables	4%
Transformer station	2%	Traffic Control/HSE/Project Management	4%
Scour protection	5%	Installation part of hardware cost	

The turbine is 50% of the cost and here seem very few synergy possibilities for combinations with other types of offshore installations.

The wind turbine foundation might for future installations be shared as example with wave energy and/or aquaculture farms. The total foundation cost are 15% for the hardware and 5% for the installation, this means for an optimal case in total 20% to be shared in a combined installation.

Cabling is 15% hardware and 4% installation. If a MUP is including combinations of wind with wave and/or tidal energy will the cabling cost make a specific potential for synergies. However for MUP´s in combination of energy production with aquaculture this synergy seems much less - if existing at all.

Cost for scour protection are 5% and might in some special situations contain synergy effects, if boats, divers and handling equipment can be shared between the different part of the MUP platform.

Installation time for an offshore wind farms are in the order of one year.

3.3.2 Installation of aquaculture farms

In question here are different kind of food and biomass production. Fish cages might be dominant today, but shell fish production and seaweed cultivation on lines must also be considered.

For fish cages the dominant components are the circular fish cages (typically with a diameter of 100 meter and a depth of 20 meter or more). The weight of such a cage might be 50 tonnes, when the mooring system for a sample of 5 - 10 cages might have a weight of 75 tonnes. The fish cages will be assembled on- or nearshore and towed to the offshore site. The needed crane capacity for offshore work will be limited to 5 - 10 tons. Installation time for an aquaculture farm will be less than one month.

The shellfish production consists of subsea lines. These lines are connected to the sea bottom through a mooring system. Installation time will be less than a week.

The seaweed culture might grow upon horizontal wires stretched 5 - 10 meters above the seabed, and linked to the bottom of the sea (Fig. 3.2).

See also these questions about installation of aquaculture equipment handled in reference [17].

It is likely to assume that the construction of a wind/aquaculture farm not will take more time than would be required when building the wind farm and the aquaculture farm separately. Some minor synergy effects (seen from the aquaculture side) for the installation phase seems possible and installation activities might be carried out simultaneously, however it must also be considered that the two activities might create disturbance for each other.

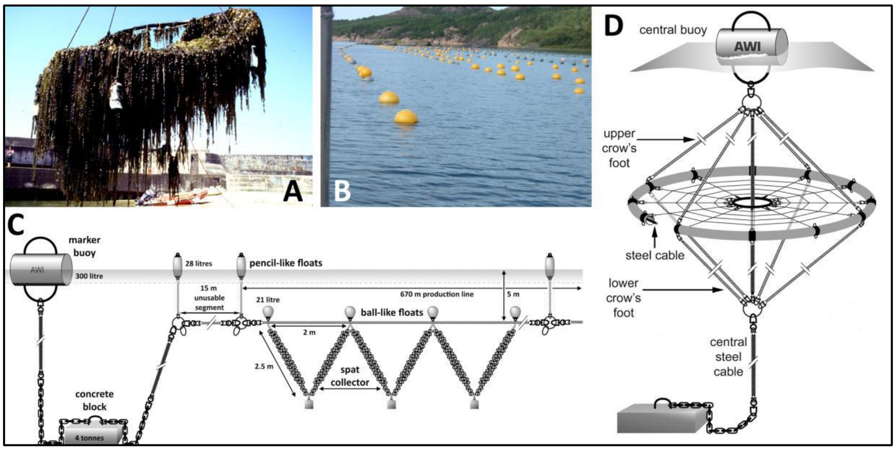

Figure 3.2 Installations for Seaweed

3.4 Operation and maintenance (O&M)

A wind farm combined with an aquaculture farm might hypothetically result in a number of barrier effects, since the earlier open wind farm now will be crowded with fish cages, longlines etc.

A potential concern might be that more seabirds are attracted by the aquaculture farms which may result in increased bird collisions for the wind farm.

Also seals and sea lions might be attracted by increased food availability, in particular fish.

Regardless whether the operation of a wind farm or of an aquaculture farm is concerned, both farms require maintenance, involving transport by vessel and/or helicopter. These activities cause various disturbances like underwater noise, marine litter, introduction of contaminants, and visual disturbance. If synergy advantages can be achieved through a share of transport and access facilities, e.g. when maintenance activities in the wind farm and the aquaculture farm can be carried out in a same window of opportunity, it may be assumed that compared to single-use less potential disturbances occur, since a vessel then needs to make the trip from the coast to the farm only once.

As described earlier the operation and maintenance for offshore wind typically amounts to 25-30% of the total lifecycle costs of offshore wind farms [15]. If the combination of offshore wind energy and offshore aquaculture proofs to be feasible and profitable in practice, there might be an additional possibility to reduce the O&M costs by synergy effects of the combined operations.

To get more insight in the O&M cost structure of OWFs, the total O&M costs according to [18] are split over specific O&M disciplines. It starts with the breakdown of the operational expenditures (OPEX) (see Fig. 3.3).

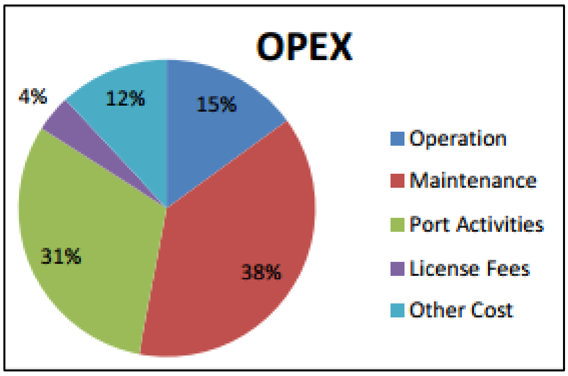

Figure 3.3 Breakdown of operational O&M cost for offshore wind farm (from reference [18]).

This breakdown shows that the O&M costs represent 53% of the total OPEX (15% “Operation” + 38% “Maintenance”). According to reference [18] the “Maintenance” is considered to be the combination of all technical, logistic, administrative and managerial actions during the life cycle of an object.

Annual O&M cost for offshore wind farms has been validated in many reports and the spread in Fig.3.4 illustrates the result obtained from sources like [14], and [18-22]. Annual O&M cost varies between 15 and 45 €/MWh. Size of the wind parks and distance to the shore do have great influence on these numbers, but unfortunately this information is not a part of the named reports. An average (orange line) is determined to 30 €/MWh (or 3 cent/kWh).

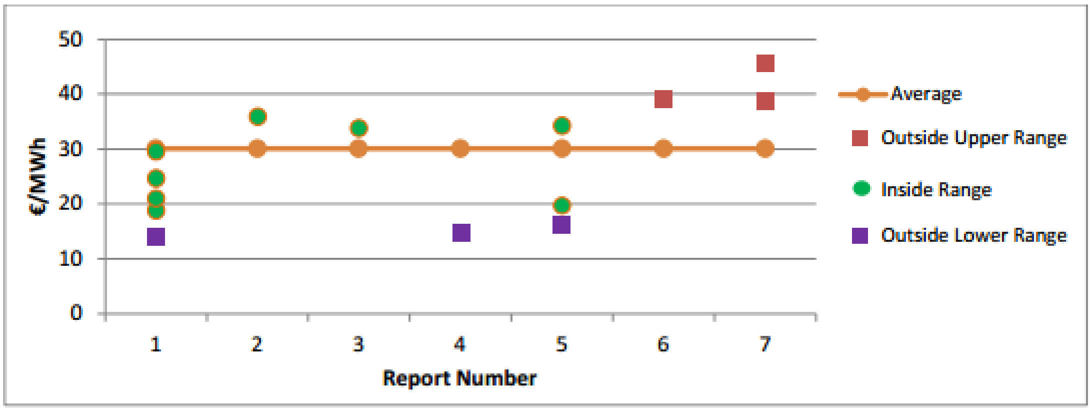

Figure 3.4 Spread of O&M cost for offshore wind farm (based upon seven different studies, [18]).

To estimate the potential synergy through combining wind and aquaculture farming, the following assumptions apply:

3.4.1 Operations & Life Cycle Management

For large OWFs it is common to have a control room ashore, 24 hours and 7 days a week staffed by two to four people. This control room may not be placed near the site, but can be at a central place. It is assumed this team also can manage the farm for aquaculture, if it is integrated in the wind farm environment.

3.4.2 Maintenance and Improvements

Previous studies and practical experiences until today [23] have shown that in general 50% of the charged maintenance labour are non-productive time because of waiting for weather windows, certified personnel, transport opportunities, necessary tools and equipment (the 50% will probably be reduced into the future).

For reduction of waiting time, seemingly there are several logistical opportunities for synergy. For example, when a multi-purpose ship sails out for a week to transport a maintenance crew to and from the wind turbines, it can inspect the aquafarm installations feed the fish and maybe harvest fish/mussels, while the crew is busy carrying out the maintenance work. When tasks are finished, the ship takes the crew on board again and brings crew and harvest ashore.

In reference [19] it is assumed that by combining wind energy and aquaculture production these ‘lost hours’ can be reduced up to 25% of the charged maintenance labour. This means that, when the labour cost is 60% of the total O&M cost of a wind farm, a cost reduction of up to 15% here should be attainable.

Overall taken this will, according to [19] lead to an overall reduction of O&M costs up to 10%. The below listed cost breakdown (in % of the total O&M cost of wind energy) is according to the same source [19] considered to be a reasonable estimation for an offshore wind farm and the combination of offshore wind and aquaculture farming. The actual MUP combination is "wind- and mussels farming", but it seems not unrealistic that the figures also might cover other aquaculture elements. One uncertainty is whether disadvantages have been subtracted from the numbers (as example cost for sharing same HSE requirements and rules).

Table 3.2 Estimation of cost shares for wind farming when carried out singly and in combination with mussel farming, based on the Dutch expert workshop [19].

O&M Disciplines	Wind farming	Combination of wind & aquaculture
Operations	11%	9%
Life Cycle Management	7%	6%
Inspective Maintenance	10%	9%
Preventive management	12%	11%
Corrective Maintenance	35%	32%
Improvement	25%	23%
Cost reduction	-	10%
Total	100%	100%

3.4.3 A shared common infra structure

To connect an offshore wind or wave park to the electric grid (usually onshore) represents one major cost driver for marine energy arrays. Therefore, a combined production of electricity using a shared electric connection would become an important factor for cost reduction. This however largely depends on the actual load-pattern of the combined wind/wave output.

Electric grid is a necessary part of the offshore energy sector (wind, wave, tidal), but not for the aquaculture industry. Some minor synergies, special for the offshore aqua industry might exist here.

3.4.4 Shared substructure foundation system

One alternative to combine wave and offshore wind within a single array is a hybrid design. Hybrid wave converter systems share the same substructure or foundation with the offshore wind turbine. This shared cost will lead to an important cost reduction, as the substructure represents one of the most important costs of an offshore project.

Another possibility for the combination is a wind turbine on jacket foundation combined with a fish farm. In reference [24], a quite upside down solution is described for this - using the area inside the jacket construction for the aquafair activity. A dual-use of the jacket foundation of wind turbines for both energy extraction and aquaculture farming. Fish will be housed within a jacket foundation that is covered by fishnets. Due to the dual-use, the cost of the Jacket-Cage seems to have a potential to be competitive with the conventional fish cage. According to reference [25] the annual yield from the co-use increases by 44% compared to the pure offshore wind farm. It is obvious that the operation and maintenance of the fish farming here has the potential to use the existing facilities from the offshore wind farm, and to create new effective aquaculture functionality, but more detailed analysis have to reveal if barriers exist that will make such solutions problematic.

3.4.5 Support ships, helicopters etc. for combined support of Offshore Wind and Fish Farming

If offshore accommodation not is a possibility for a MUP installation, then support ships (Fig. 3.5) are very important to attain the demonstrated 10% savings on O&M costs. These ships might even function as a hotel ship for a 24/7 service beside the MUP platform, including storage for tools and equipment for service & repair of wind farms and food for a fish farm. According to [19] the design requirements of these ships must live up to transport possibility for at least 30 - 50 persons and wind farm plus aquaculture spares and further eventually food for fish, and some equipment for harvesting the aquaculture farm etc.

Figure 3.5 Mother ship for off-shore wind.

The ships will operate at harsh weather conditions and must be equipped with work tolls like a motion compensated crane, dynamic position systems etc. Further it must be a comfortable platform to live on for at least one week even with significant wave heights. If possible this ship should be able to operate in a weather window up to 95% over the year (for North Sea conditions).

As mentioned many times before the offshore environment is harsh, and offshore wind turbines require service visits almost every second month (will be reduced to two to three visits per year in the future). Operation and maintenance (O&M) visits are carried out by large vessels for scheduled service in combination with helicopters for unscheduled work.

Until now, O&M visits are preferred to be carried out by boats when the significant wave heights should be less than or equal to 1.5 m. According to [19] each support vessel has a certain maximum allowable significant wave height. Therefore, the availability of a vessel is correlated with the occurrence of certain significant wave heights. Developers and offshore service providers are therefore looking for new methods, one of which is the 'mother ship' approach. A single large vessel would then service one or more offshore wind farms staying in the neighbourhood of these farms for long periods of time and deploying multiple smaller craft for daily servicing.

3.5 Risks of MUPs

3.5.1 Three major risks of the fish cages within the offshore wind farm

There are many advantages for the aquaculture farming to occur within an OWF. However, there are also risks from the MUP approach.

There are at least three major risks related to the implementation of conventional large fish cages within the offshore wind farm. First, most conventional fish cages and their mooring systems have been designed for operation at inshore protected sites. Unfortunately, these fish cages and mooring systems might be damaged under the harsh conditions of offshore wind farm sites, where typically high wind speeds and high wave amplitude can have deleterious effects. The submersible fish cage has been developed to avoid the damages under the bad weather conditions; however, it increases the cost and the complexity of the O&M, and reduces the fish cage operational reliability.

Second, the fish cages with their mooring systems placed within the OWF might increase collision risks with the operation, service and large maintenance vessels. This is possible despite the large space between the wind turbines.

Finally, there are conflicts between the offshore wind and aquaculture farms during the installation and operation phases. During the installation phase, there are many parallel installation operations to reduce the installation period; and this is crucial for the cost reduction and minimizing environmental impacts. During the operation phase, the complex logistics of the aquaculture farming might increase the risks to the O&M of the offshore wind farm. Moreover, jacket corrosion and the marine biofouling growth on the jacket must also be studied. Another potential risk might be that the fish in the cages will attract avian predators which may increase bird mortality due to collision with the turbines or support structures.

The operation of the wind turbine may affect fish in a variety of ways. The impacts include reflecting light, shadow effect, noise and electromagnetic fields. The turbine rotation also results in vibrations of the Jacket-Cage.

Many more risks resulting from the MUP should be identified during the installation and O&M phases. Problems related to the licensing, policy and the sharing among the different stakeholders might appear which are not addressed in this study.

3.5.2 Other risks

Problems related to the licensing, policy and the sharing among the different stakeholders might appear.

One major concern/risk for the MUP platform is increased complications due to the combination of two or more quite different processes for planning and operation. Each off-shore activity is a commercial activity, so all precautions must be taken for an optimal economic case. Each part therefore has made all efforts to optimize the planning of both the installation process as the following operation of their off-shore plant. And these efforts are built in systems that each part follow in their daily work.

If suddenly each part has to pay attention to corporation with a new part for both installation and operation, the end result most likely will be a more expensive and troublesome planning of the future work. There might be some synergies that could bring down some costs, but so far of minor importance for the complete economic calculation of the total MUP platform.

One major issue that will come up in this corporation is how to solve the priority problem. What is most important - to service a wind-turbine or to feed a fish farm? Questions of that kind inevitably will show up, and the answer not given here, but the priority problem will be an important issue.

Different mind sets for the involved parts must be solved. As example has the wind industry very strict demands for security and education for the involved crew. If common operation should be made with other off-shore industries, they will have to follow the demands for the wind industry.

The examples given above are only a few of the risks/difficulties that will show up if a MUP platform - with different owners - should be established. A lot of risks exist, but the major barrier so far seems to be lack of open-minded willingness for the different parties to operate together.

Another consequence from a lack of practical experience when dealing with combined technologies, is the lack of knowledge for insurance cost.

This question has often been raised and seems so far to be of major concern.

Further research and development is necessary on key technology components such as, new materials for mooring lines, new concepts of mooring systems, anti-collision systems to avoid damage of the wind turbines in the event of mooring failure and minimise the collision risks. Further is a need of development for full scale concepts of combined technologies to prove the validity of the synergies and their economic impact on a real project, and to understand the possible physical interaction between the offshore technologies in question.

4 Ecological Considerations for the Construction and Operation of case study MUPs.

The designed MUPs for the MERMAID project include aquaculture production at four sites. Selection of species is dependent on location and therefore varies between the four sites. The ecological impacts of a fish farm are illustrated in Fig. 4.1. Construction of a MUP can have temporary and long-term impacts on the hydrodynamics and ecology of an area. The level, frequency and duration of impacts depend on the type of operations and the ecosystem sensitivity to changes. The potential ecological impacts of an MUP should take into consideration underwater effects and any above sea level impacts and including construction and operation phases. For discussions related to ecological aspects of MUPs refer to the deliverables in WP 4 in this project.

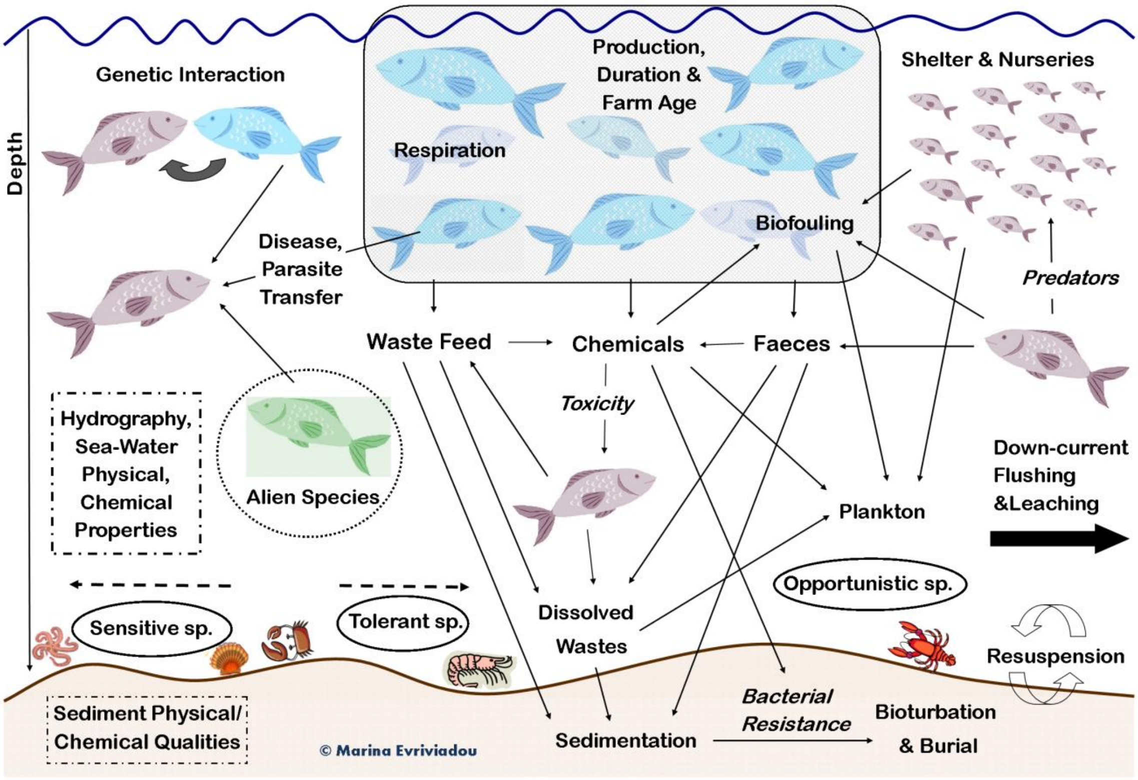

Figure 4.1 Possible ecological impacts of fish cage farming, taking into consideration the water column, bottom sediment and wild population interactions.

5 Conclusions

In the two study cases, first, the annual electricity yield of the offshore wind farm has been estimated along with an integrated aquaculture production. The large area contained within the wind farm has the potential to create a high revenue aquaculture production (Salmon/Sea Bass, mussel and seaweed). This presents a promising opportunity to improve the economics of the offshore wind farm. Second, for the fixed foundation WTG, the installation of a 10 MW jacket foundation is executed by a new generation installation vessel with dynamic positioning abilities. An ambitious installation schedule of one year for a 1000 MW offshore wind farm has been presented. For the floating WEG, the fully assembled floating 10 MW WTG is towed to the final operation site. The third aspect covered in this paper is the aquaculture systems, including the installation, operation and maintenance of fish cages, blue mussel production lines (drops) and seaweed production systems. The final aspect of this paper addressed the risks from the MUP towards aquaculture production.

In conclusion, this MUP case study has demonstrated the promise of ocean space co-use though it also beckons the technology development of the aquaculture farming under harsh offshore conditions. The aquaculture farming facilities within the offshore wind farm must be taken beyond the experimental level and the technology development under offshore harsh conditions would be subsequent challenging tasks [25].

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