# MERMAID

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# Deliverable: D 6.2 Multi-Use Platform (MUP) Business Case

Including energy extraction and aquaculture farming

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

### Task 6.1 Set-up a Multi-Use Platform study case

| Deliverable: D 6.2 Multi-Use Platform (MUP) business case | |
|---|---|
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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 |
| FIV | : | Floating Installation Vessel |
| OWF | : | Offshore Wind Farm |
| O&M | : | Operation and Maintenance |
| WEC | : | Wave Energy Converters |
| WFSV | : | Wind Farm Service Vessel |
| WTG | : | Wind Turbine Generator |

# Summary

The deliverable "D6.2: Multi-Use Platform (MUP) Business Case" provides an example of a MUP for co-use of ocean space. It combines an energy extraction farm and an aquaculture farm. This MUP case study focuses on four aspects: MUP layouts and estimation of the increased yields; installation of 1000MW offshore wind farm (100 units of 10MW wind turbines), installation of aquaculture facilities; and the synergies and risks from the different deployments and operations of a MUP. This proof-of-concept case study is based on site conditions at a North Sea and an Atlantic site, but modifications are introduced to address the future challenges of installation, Operation and Maintenance (O&M).

For the first aspect, the two MUP layouts have been proposed at two different water depths: a jacket foundation for a wind turbine generator (WTG) at 40m depth (North Sea site) and a floating WTG at a depth higher than 100m (Atlantic site). The two layouts require an area of 138km² (North Sea site) and 228km² (Atlantic site). The large area contained within the wind farm has the potential to yield high revenue aquaculture production (e.g.: salmon/sea bass, mussel and seaweed). The 1000MW offshore wind farm results in annual wind power production and yield of 3 300GWh and 471 M€ (0.14€/kWh) for both cases. The potential annual salmon production and yield are 60 000 to 70 000tons and 240 to 280M€ (€4/kg) for the North Sea case, while the annual Sea bass production and yield are 90 000 to 105 000tons and 360 to 420M€ (€4/kg) for the Atlantic case. This fish farming yield can account for 50 – 60% (North Sea) and 76 - 89% (Atlantic) of the annual electricity yield. The mussel and seaweed production systems will further increase the yields and potentially absorb fish dissolved wastes. The MUP which includes wave energy converters delivers more power and has the potential to deliver more stable power.

In the second aspect, more efficient installation methods of a 10MW WTG are proposed. A floating installation vessel is selected as an example to conduct the two sequential operations of the installation of jacket foundation: pre-pilling using a template, followed by jacket installation. The 10MW WTG is installed by a jack-up vessel using four lifts: lower tower; upper tower; nacelle; and rotor with hub and blades. Additionally, the installation of the substations and the cables is described. An ambitious installation schedule of one year for a 1000MW offshore wind farm at the North Sea site has been presented. In the case of the floating 10MW WTG, the fully assembled WTG is towed to the final operation site.

The third aspect covered in this report covers the installation of aquaculture systems, including fish cages, mussel production lines and seaweed production systems. The vessels necessary for the O&M of an offshore wind farm and for the fishing farming are also discussed.

The final aspect addresses the synergies and the risks of combining various deployments and O&M operations of a MUP. The quantitative evaluation of the synergies and risks of the proposed MUP compared to a 1000MW wind farm will be presented in the following deliverable D6.3.

In conclusion, this MUP case study has demonstrated the promise of ocean space co-use. This study also beckons subsequent work into technology developments for the implementation of aquaculture farming under harsh offshore conditions.

# 1 Introduction

## 1.1 Motivation and Objectives

The offshore wind energy industry faces many new challenges. Firstly, an offshore wind farm (OWF) ties up a large area and this might have a deleterious impact on fishing or other activities in the region. For example, in the UK the OWF project Dogger Bank (capacity permission: 9GW and estimated capacity: 7.2GW) ties up an area of 8660km2 [1]. Second, the cost of offshore wind farms located in deeper water or far offshore sites requires innovations and technology breakthroughs centered on dual-use technologies in order to justify development expenditures.

Co-use of ocean space with the fisheries industry through the production of aquacultured species inside or near the area of the wind farm, is suggested as a possibility for reducing potentially negative effects of tying up large marine areas. Additionally, aquaculture production will be increasingly important in meeting the growing gap between supply and demand for seafood products. Use of exposed and remote sites will enable a growth in the fisheries industry sector. It is also expected that the level of conflict with other stakeholders, such as tourism and transport along with environmental concerns, will be smaller at exposed off-shore sites compared to more sheltered coastal areas.

The EU collaborative research project "Innovative Multi-purpose off-shore platforms: planning, design and operation" (MERMAID) aims at the multi-use of ocean space for energy extraction, aquaculture and platform related transport [2]. However, there are many bottlenecks related to the various deployments and operations of Multi-Use Platforms (MUPs). Accordingly, work package 6 in MERMAID explores 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.

The synergies and the disadvantages of the MUP compared to an OWF will be reported in deliverable D6.3 [2]. The MUP will be evaluated with regards to three criteria: yield, cost and impact on the marine environment. In deliverable D6.3, 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 and the Proposed MUP Case Study

The MUP case studies described here are located at a North Sea site with fixed foundation and at an Atlantic sea site with a floating WTG installation. 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 three goals of the proposed MUP case study are listed as follows.

- Propose technical solutions to installing large 100MW OWFs and various species aquaculture farms
- Address the challenges of the installation methods for large WTGs (10MW) and faster installation methods to reduce the installation period.
- Analyse the synergies and the conflicts of MUPs during installation and O&M

## 1.3 Potential for Offshore Wind Farm Co-Use of Space with Aquaculture

The proposed MUPs in this report include the energy extraction of a 1000MW wind farm (100 units of 10MW WTG) (Fig. 1.1), a wave farm and an integrated aquaculture farm for co-use the ocean space [3]. The OWF has two offshore substations and the WTG units are installed either on a jacket foundation or are a floating design. A 1000MW farm (100 units of 10MW) can occupy a bottom area of 138km², but the actual footprint is only 1% of the farm surface area [2]. A 10MW wind turbine has a rotor diameter of nearly 200m, while the distance among turbines is 1600m in one direction and 1200m in the other direction (Fig. 1.1). The distance between turbines is dependent on WTG size; the larger the turbine, the bigger the distance. Consequently, there is great theoretical potential in large OWFs, in the distance between turbines to co-use ocean space with aquaculture farming.

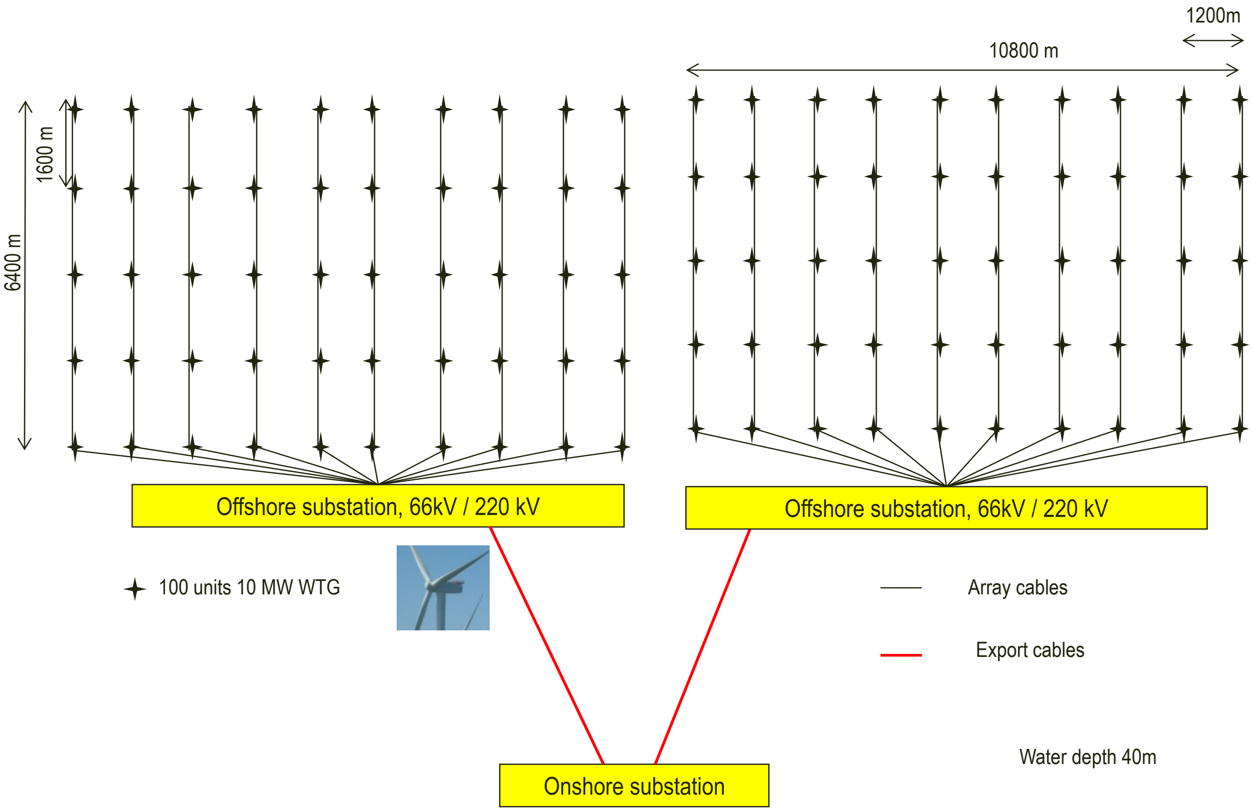


**Figure 1.1** Layout of a 1000MW (100 units of 10MW) wind farm (North Sea case study)

## 1.4 Case Specifications and Site Conditions

The MUP site conditions in this report are based on the four MERMAID pilot study sites (Fig. 1.2) with different environmental characteristics [2]. The site conditions (wind and wave energy) of the four sites are described in Appendix C.

1. Active morphology site, in the trans-boundary area of the ***North Sea-Wadden Sea***;
2. Deep water site, in the ***Atlantic Ocean***;
3. Sheltered deep water site, in the ***Mediterranean Sea***;
4. Estuarine area, in the ***Baltic Sea***.

The four deliverables for the four MUP cases, at the four project-specific sites, are due to be delivered at a late phase of the MERMAID project.

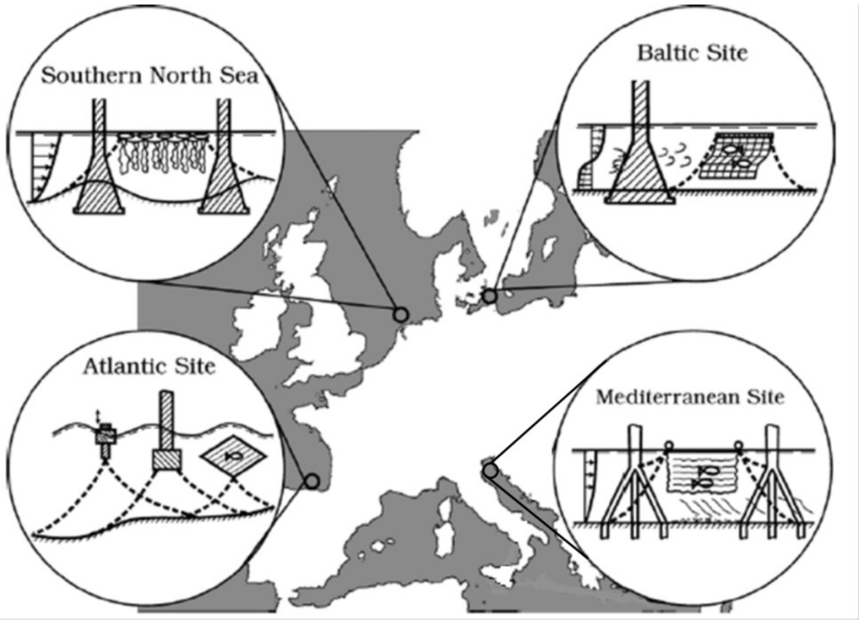


**Figure 1.2** Location of the four wind farm and aquaculture integration sites, as defined in MERMAID

Please note that this MUP is not project-specific. Variations and assumptions are introduced in order to consider future challenges to be faced at OWF sites. More specifically, the North Sea site conditions in the MUP case study are based on the Gemini site in the Netherlands (Appendix B), with modifications including the Dogger Bank site conditions and offshore challenges (Appendix A); this will help address the future challenges of transportation, installation and O&M of an OWF. For example, the Dutch Gemini OWF will commence the construction of a 600MW farm in 2015, while the developers of Dogger Bank are still exploring cost effective business development plans. In addition to the OWF, at the deep water site (Atlantic Site) the different installation technologies of floating WTGs will be briefly discussed.

## 1.5 Work Scope

The installation of a typical OWF study case (Fig. 1.3) includes the following four types of components in summary:

- Wind Turbine Generators
- Two types of WTG fixed foundations: jackets (Fig. 1.4A) and monopiles (Fig. 1.4B); and two types of floating WTGs : WindFloat (semi-submersible) (Fig. 1.5A) and Hywind (spar) (Fig. 1.5B)
- Transformer Substation (Fig. 1.5C)
- Cables (Fig. 1.4C)

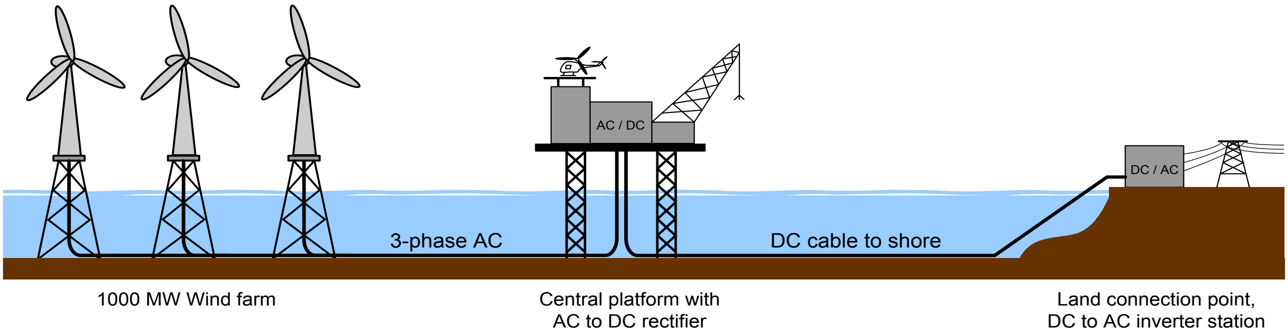


**Figure 1.3** Layout of the components of an offshore wind farm

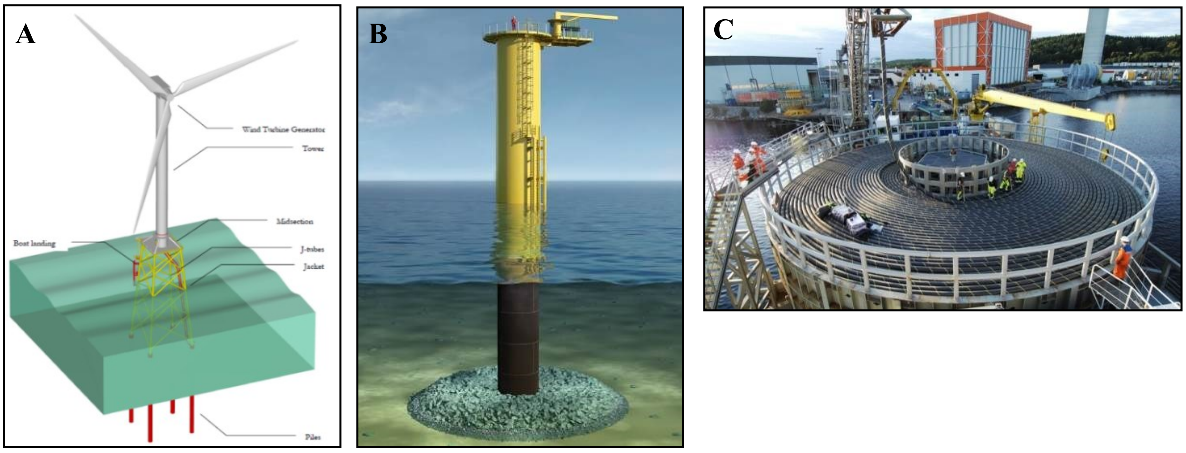


**Figure1.4** Jacket foundation **(A)** Monopile foundation **(B)** and the Installation of cables **(C)**

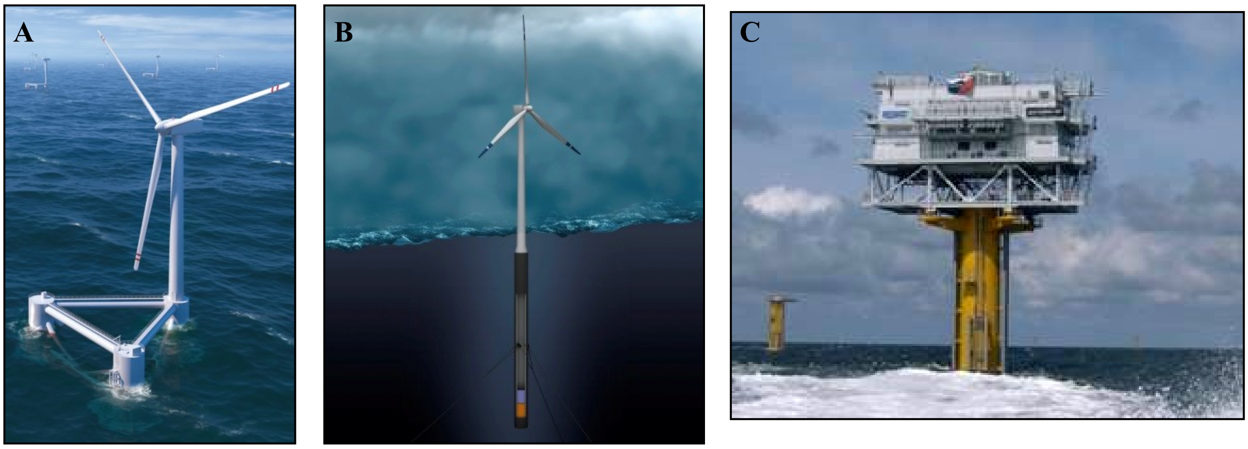


**Figure 1.5.** Floating WTGs WindFloat **(A)** and Hywind **(B)** and **(C)** an OWF Substation

Three types of wave power units will be briefly discussed and are as follows:

- Wave Star (bottom fixed) (Fig. 1.6)
- Pelamis (floating attenuator)
- Floating Power Plant / Poseidon (combined wind/wave)

**Figure 1.6** Bottom fixed wave power unit Wave Star [6].

The three types of aquaculture farm units briefly discussed are as follows:

- Fish cages (Fig. 1.7)
- Mussel line (drops) system (Fig. 1.8A)
- Seaweed production system (Fig. 1.8B)

The different units will be further described in the remaining report.

**Figure 1.7** Typical round fish cage

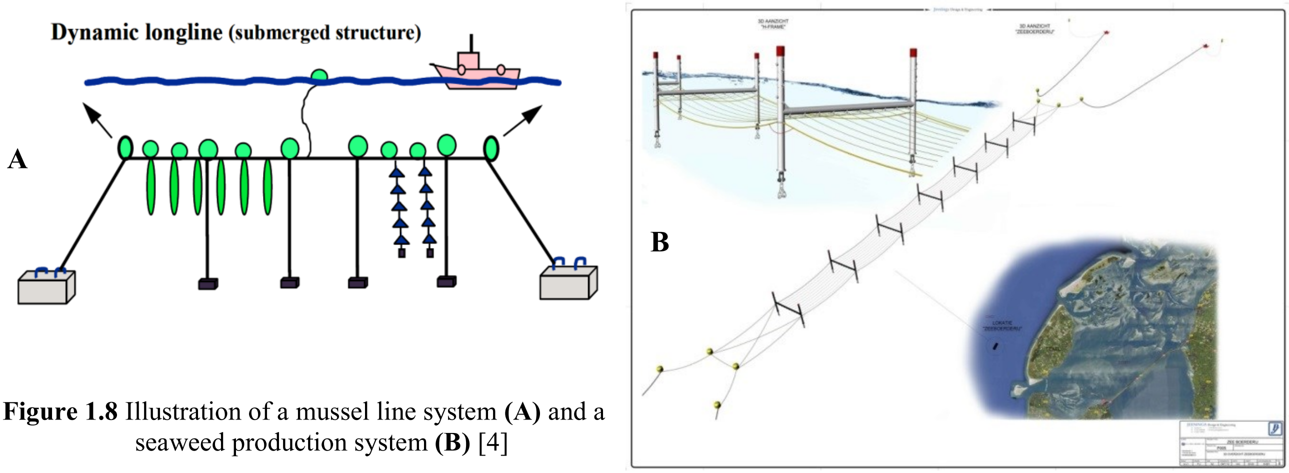


**Figure 1.8** Illustration of a mussel line system **(A)** and a seaweed production system **(B)** [4]

This report with its appendix is to fulfil deliverable *D6.2 MUP Business Case* as defined in EU MERMAID [2]. Chapter 2 presents the MUP case study at the North Sea site and Chapter 3 will address the installation of the floating wind turbines at the deep water Atlantic site. The summary of the 1000MW wind farm installation at the North Sea site and the Atlantic site, along with the synergies and the risks of a MUP are highlighted in Chapter 4.

Ten Appendixes supplement this main report. Appendix A introduces the MUP assumptions at the North Sea Site, while Appendix B describes the Dutch OWF Genimi. Appendix C briefly gives the wind and wave energy information of the four MERMAID MUP sites. Appendix D gives an overview of the transportation and installation methods for monopiles and Appendix E the installation of the floating WTG Hywind. Appendix F provides a literature review of the service vessels for OWFs. Appendix G describes the O&M of the Sheringham Shoal OWF, while Appendix H assesses the weather windows available at the North Sea site. Finally, Appendix I and J show two publications of the MUP case study.

The MUP results aim at providing a basis for the MUP designs and studies in Work Package 7 [2]. Please note that the MUP cases at the Mediterranean Sea and Baltic Sea sites are not studied in this report. If the wind farms and aquaculture facilities at the Mediterranean Sea and the Baltic Sea sites use similar WTG units or aquaculture fish cages like at the North Sea or Atlantic sites, the transport technology presented for the North Sea and Atlantic sea sites can be applied. If new transport technologies are required for the wind farm or aquaculture farm at the Mediterranean Sea and/or the Baltic Sea site, these will be addressed by the following deliverable D6.3 report: The synergies and disadvantages of MUP.

# 2 MUP Case Study at the North Sea Site

## 2.1 Characteristics of the Site

The North Sea site (Fig. 2.1) is located in the southern North Sea approximately 53km (or 30nmi) North West from the Dutch city of Delft. The site is characterized by average water depths of approximately 40m and it is an area of heavy swells and winter storms. Salinity varies between 30 - 35‰ and sea water temperature ranges from 3 - 20°C. The concentration of chlorophyll in the area is affected by nutrient rich coastal waters and varies between 2 - 8µg/L. [3.1, 3.2].

**Figure 2.1.** North Sea site location (45º02′24.71”N; 7º08′34.72”V)

## 2.2 Description of the Theoretical MUP Case Study

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.

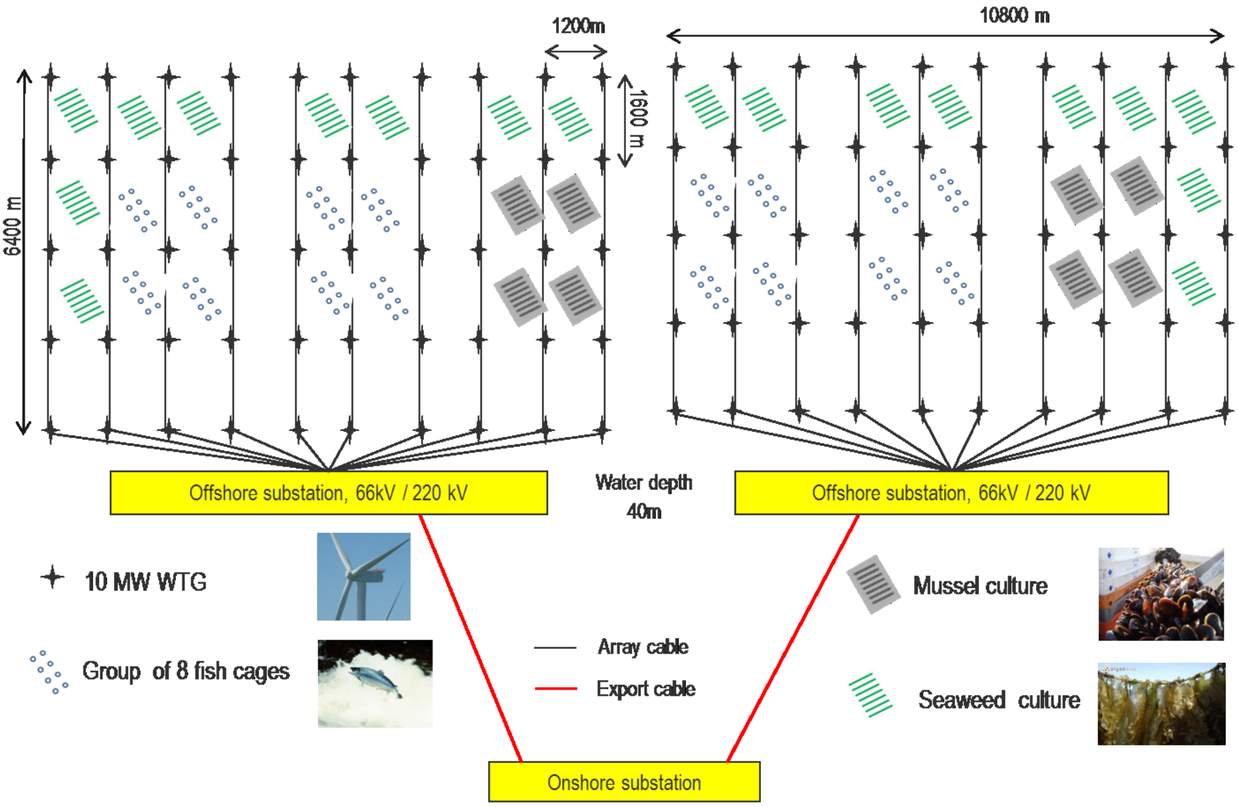


**Figure 2.2** Layout of the 1000MW offshore wind farm, integrated with aquaculture farms at the North Sea site

The base case of the proposed 1000MW wind farm is shown in Figure 1.1, 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 2.2 is a proposal for a combined mussel, seaweed and salmon production within the 1000MW OWF. For Atlantic salmon and trout, 16 units of eight circular fish cages (circumference 120m, depth 25m) will be used. There are 8 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.

## 2.3 Estimates of the Potential Production Rates and Yields

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 characteristics. The annual salmon production is 60 000 to 70 000 tons based on the fish production rate: $20kg/m^3$ (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 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 mussels and seaweed are estimated to be 20 to 30 M€ and 160 to 180 M€ respectively (at €1/kg for both the mussels and the seaweed).

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

| | Annual production | Annual yield | Comments |
|---|---|---|---|
| **Electricity** | 3 300GW/h (annual average wind speed 9.5m/s) | 471 M€<br>(0.14 €/$kWh^{-1}$) | |
| **Salmon** | 60 - 70 000 tons | 240 to 280 M€<br>(4 €/kg) | Amounts to 50 - 60% of the electricity yield! |
| **Mussel** | 20 - 30 000 tons | 20-30 M€<br>(1 €/kg) | |
| **Seaweed**<br>(e.g. sugar kelp) | 160 - 180 000 tons | 160-180 M€<br>(1 €/kg) | Attenuates waves and absorbs fish wastes |

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

## 2.4 Components of the 1000MW Wind Farm to be Installed

Technical and operational solutions for the transport and installation of foundations, WTGs, cables and substations for a 1000MW OWF will be proposed. The dimensions and the weight of the four types of components are estimated in this following section.

### 2.4.1 Jacket foundation

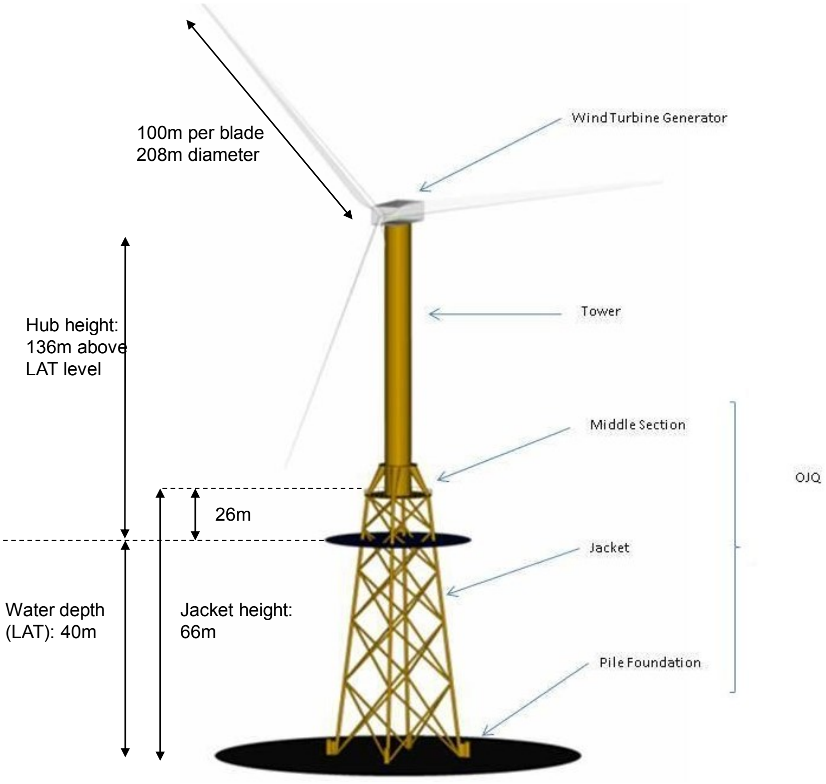


**Figure 2.3** Example of a wind turbine generator, with a jacket at 40m water depth, used in the study case

Each 10MW WTG is installed on top of a jacket foundation using four piles as illustrated in Figure 2.3. The jackets to be installed at 40m depth have the following assumed dimensions:

**Table 2.2** Dimensions and weight of a 10MW jacket foundation

| | **Wind turbine size** | **10MW (estimation)** |
|---|---|---|
| **Jacket** | ***Dimensions*** | L*W*W: 66 * 27m * 27m |
| | ***Weight*** | 1000 ton |
| **Piles** | ***Dimensions*** | L*D: 50m * 2.5m |
| | ***Weight*** | 700 ton |

### 2.4.2 Wind Turbine Generator components

The data for the assembled 10MW WTG components ready to be transported for installation, using the base case study described above, is provided in Table 2.3.

**Table 2.3** Details of the WTG components

| WTG component | Dimensions | Weight (tons) |
|---|---|---|
| **Nacelle** | 19m * 6m * 7m | 700 |
| **Hub** | d = 8m | 100 |
| **Blade** | 100m * 6m | 30 |
| **Tower section 1** | 55m * d = 8m | 280 |
| **Tower section 2** | 55m *d = 6m | 220 |

### 2.4.3 Substation

Four types of substations are shown in Figure 2.4. The jacket-up/self-installing platform substation (Fig. 2.4D) is selected for this case study, since no heavy lifts are needed during installation.

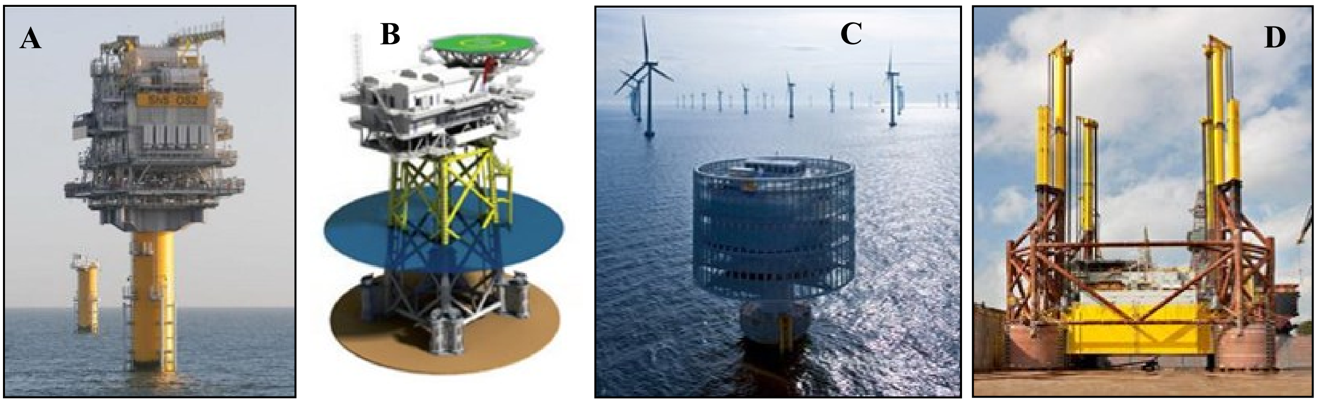


**Figure 2.4** Substation types: Monopile Foundation (**A**), Jacket Foundation (**B**), Gravity base (**C**) and Mobile jack-up/self-installing platform (**D**)

The dimensions and weight of two substations for a 1000MW OWF are provided in Table 2.4. Two self-installing platforms will be utilized as substations for this case study.

**Table 2.4** Details of substation components

| Component | Dimensions | Weight (tons) |
|---|---|---|
| **Topside/platform** | 42m * 42m * 15m | 4 500 |
| **Substructure** | | 2 300 |

### 2.4.4 Cables

There are two types of cables: array cables and power export cables. There will be in total 100 infield cables installed for the 1000MW OWF. This includes 20 cables from WTGs to the substation, assuming that 5 WTGs are placed on each row. The cable lengths will be 1.2km and 1.6km between the WTGs and the length from the WTGs to the sub-station. Two export cables will be installed, one from each substation to shore and with an approximate length of about 100km.

## 2.5 Installation of a 1000MW Offshore Wind Farm

This MUP case study investigates the installation of future large 10MW WTGs. In this study, a new generation of Floating Installation Vessel (FIV) is selected to conduct the installation of the 10MW WTG foundations; the NorWind Installer will be used as an example in all figures. The installation is performed in two operations: pre-piling and jacket installation. Standard jack-up vessels are utilized for the WTG installation operations.

### 2.5.1 Installation of the Jacket Foundation

The installation of the 10MW jacket foundation is performed in two sequential operations: pre-piling followed by jacket installation. There are four piles and the total weight is 700tons. Each pile is 50m long with diameter of 2.5m. The jacket foundation is designed for a water depth of 40m, has a height of 66m, a footprint of 27m * 27m and the weight of 1000tons.

The installation of the jacket foundation shown in Figure 2.5 follows the following six steps:

- Placing the piling template (Fig. 2.5A)
- Placing the foundation piles and drilling them in place (Fig. 2.5B and C)
- Retrieving the piling template (Fig. 2.5D)
- Lifting the jacket substructure and placing it on top of the piles (Fig. 2.5E)
- Grouting the foundation piles (Fig. 2.5F)

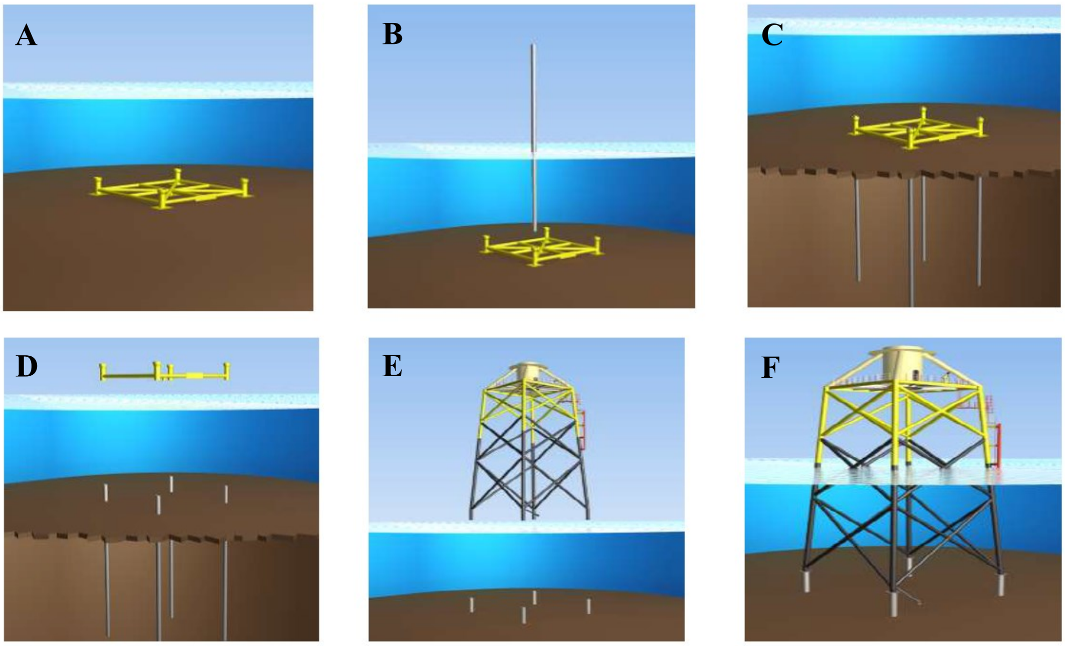


**Figure 2.5** Illustration of the template pre-piling method for the installation of jacket foundations.

### 2.5.2 Piling jacket foundation installation vessel

FIVs are equipped with Dynamic Positioning (DP) and are designed for world-wide operations, with a focus on pre-piling and jacket installation for the offshore wind industry in North Europe. Different deck layouts have been developed for various installation modes (piles, jackets, etc.) on top of the generic vessel platform provided by Ulstein Sea of Solutions. The vessel’s dynamic positioning capabilities are considered to be state of the art for subsea construction vessels.

The FIV used for pile installation should be designed for maximum efficiency and cost effectiveness, it features a 1000ton heave compensated offshore crane on the starboard side, while a pre-piling template can be located on a support structure at the stern. The vessel, piling mode illustrated by Figure 2.6, can also be converted into a jacket installation mode (for jackets up to 800tons) with deck rearrangement (lifting equipment, grillage, storage frames, etc.).

The principal dimensions of the vessel are:

| | |
|---|---|
| ▪ Length overall | ≈ 166.80m |
| ▪ Breadth moulded | 32.00m |
| ▪ Depth moulded | 13.30m |
| ▪ Designed draught moulded | 7.50m |
| ▪ On the design draught | ≈ 7 500tons |
| ▪ On the summer draught | ≈ 17 500tons |
| ▪ Deck Area (on main deck) | ≈ 2 650m² |

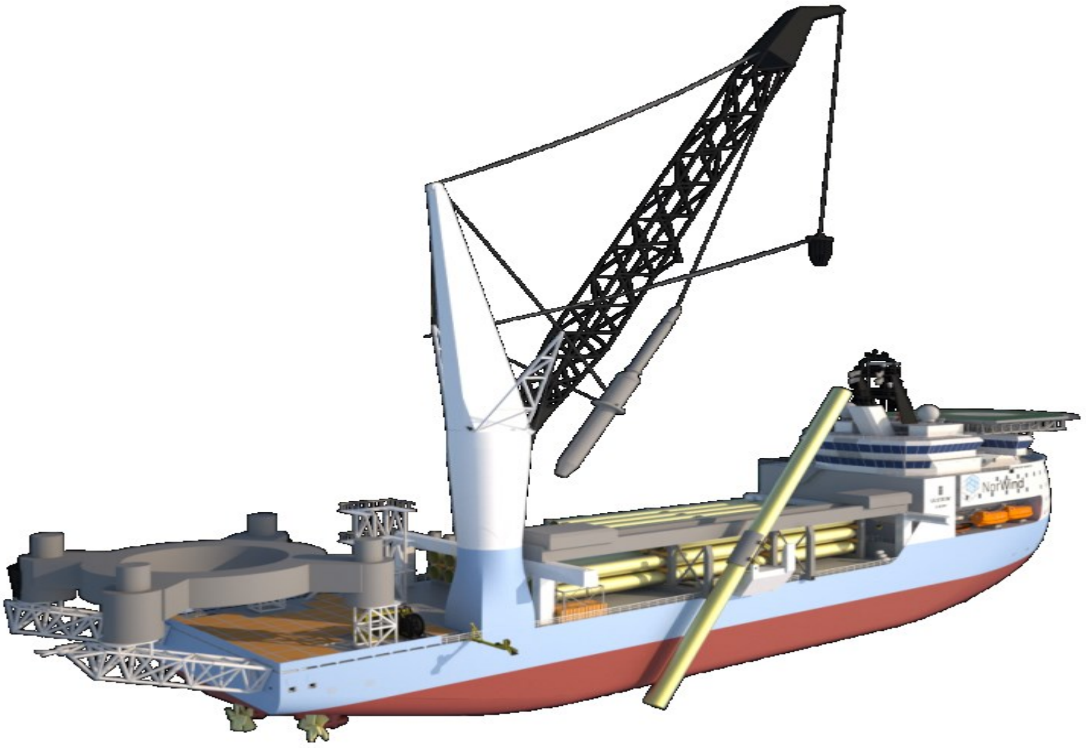


**Figure 2.6** Three dimensional illustration of the NorWind Installer vessel piling mode

For the pile installation campaign the main restriction in this case study is the Significant wave height (Hs) limit of 2.0m. Motion analysis is under development in order to verify, and possibly challenge, the above work restrictions. The pile storage capacity of the vessel for this case study is 16 piles.

Three Voith Schneider propellers of 3 900kW each will allow a service speed of 14knots and enhance the dynamic positioning capabilities of the vessel. Transit speed on a designed draught of 7.5m, on a calm and deep sea under no wind and no current conditions, utilizing 85% of the power is about 14.0knots. The vessel's travelling speed, fully loaded for pile installation, is set to 12knots in order to keep fuel consumption low and to have a buffer in the travel plan. The vessel should be kept within +/- 30 degrees of the head wave pattern in order to maintain full operability and minimise vessel motion.

### 2.5.3 Jacket Foundation Installation Vessel

The jacket installation vessel (Figure 2.7) is designed for maximum efficiency and cost effectiveness; it features a 1 500ton heave compensated offshore crane on the starboard side. The jacket storage capacity of the vessel for this case study is three jackets. To enhance vessel operability, the anti-heeling system has been designed in such a way that the main crane can revolve over 180 degrees within 5min, with a full load in its main hook; this is very advantageous for when a large jacket is on the crane hook.

The main restriction for the jacket installation campaign in this case study is the Hs limit of 2.0m. Motion analysis is under development in order to verify, and possibly challenge, the above work restrictions. Transit speed on a designed draught of 7.5m, on a calm and deep sea under no wind and no current conditions, utilizing 85% of the power, is about 13.5knots. The vessel's travelling speed, fully loaded for jacket installation, is set to 12knots in order to keep fuel consumption low and to have a travel plan buffer. The same speed is aimed for when returning to port. The vessel should be kept within +/-30 degrees of the head wave pattern in order to maintain full operability and minimise vessel motion.

Principal dimensions of the vessel are:

| | |
|---|---|
| ▪ Length overall | ≈ 162.60m |
| ▪ Breadth moulded | 37.80m |
| ▪ Depth moulded | 14.70m |
| ▪ Designed draught moulded | 7.5m |
| ▪ Max deadweight: | 28 900tons |
| ▪ Deck Area (on main deck) | ≈ 4 300$m^2$ |

**Figure 2.7** Jacket mode of the NorWind Installer vessel

### 2.5.4 Jacket installation using the Dynamic Positioning vessel

FIVs have a developed crane and deck arrangement that will enable a safe and effective handling of jackets from a dynamic positioning vessel. The jackets are tall and heavy structures and careful stability analysis is needed to provide safe operation. The vessel's capacity to handle and transport jackets on-board will vary between projects, according to jacket weights and heights. A typical deck arrangement for jackets is illustrated in Figure 2.8.

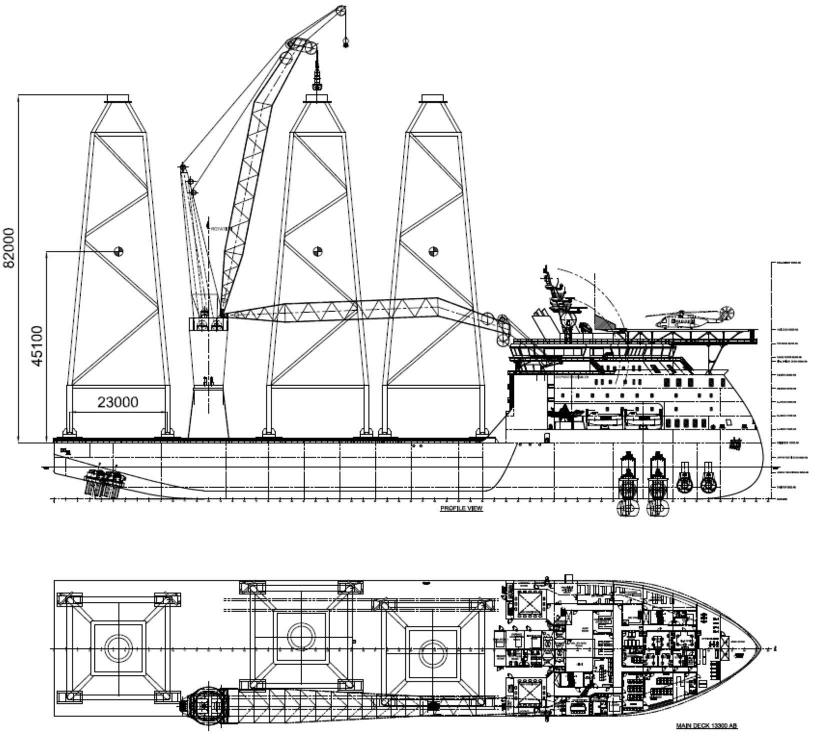


**Figure 2.8** Typical vessel deck arrangement for jackets transportation

The main installation equipment to go on-board the vessel are:

- Crane with sufficient capacity and reach for the anticipated jacket sizes.
- Skidding arrangement, incl. grillage, in order to place the jackets near the crane pedestal, for a safe lift-off from the vessel and onto the pre-installed piles.
- Remotely operated vehicle for installation assistance, during touch-down on piles.
- Jacket lifting beam arrangement, with automatic connection and release mechanisms.
- Winches to support lift-off and to avoid jacket rotation.

### 2.5.5 Jacket transport from fabrication yard to base station

The transport of the jackets from the jacket fabrication yard to the intermediate base station requires several barge-tug combinations. Based on an installation schedule where the jacket installation vessel installs three jackets over a 3-4 day period, it is critical to have an efficient feeder system that can perform without any delays; a jacket transport system is required.

The alternative is to have jacket storage on land in the near shore port and transport the jackets prior to the installation campaign start. The philosophy is that the installation vessel lifts the jackets off from the barge and onto the installation vessel, at the near shore base station/port, which in this case is located 100nmi from the offshore site.

### 2.5.6 Foundation installation

For the installation of pile foundations, the work outlined constitutes of:

a) Mobilisation of the vessel and pre-piling deck template for pile installation.

b) Pick-up the piles in horizontal position on Free Alongside Ship conditions in a nearby port.

c) Voyage from the port to the offshore site with the first batch of piles on-board.

d) Installation of the driven piles at the offshore site utilising the vessel's pre-piling template.

e) Following installation of all piles on-board, return to port to collect the next batch.

f) Repeat (b) to (e) until all piles are installed.

g) In the case where just one installation vessel is available, demobilisation of the piling template and piling equipment and remobilise vessel for jacket installation. Alternatively, a second vessel will be mobilised for jacket installation.

h) Pick-up the first batch of jackets in vertical position on Free Alongside Ship conditions at a port.

i) Voyage from the nearby port to the offshore site with the jackets on-board.

j) Install the jackets on site on top of the pre-installed piles.

k) Following installation of all jackets on-board, return to port to collect the next batch of jackets.

l) Repeat (h) to (k) until all jackets are installed.

m) Demobilise vessels in port.

It is assumed that piles and jackets are pre-transported from the fabrication site to the nearby port, where intermediate storage is provided for, prior to loading the piles and jackets on-board the installation vessel.

Cleaning and excavation of the piles will be conducted by a standard offshore vessel, prior to the arrival of the jacket installation vessel.

Grouting of the piles and jacket interfaces will also be conducted by this offshore vessel, following the installation of the jacket onto the pre-installed piles.

### 2.5.7 Wind Turbine Generator installation

The WTG installation constitutes of the following stages:

a) Mobilisation of the vessel and lifting equipment.

b) Loading on-board three sets of WTG components (tower sections, nacelle with hub and rotor blades) on Free Alongside Ship conditions, in a nearby port.

c) Voyage from the port to the offshore site with the first batch of components on-board.

d) Installation of the tower sections, nacelle and rotor blades with hub at the offshore site utilising four lifts per WTG.

e) Following installation of all 3 WTG units on-board, return to port to collect the next batch.

f) Repeat (b) to (e) until all WTGs are installed.

g) Demobilise vessels in port.

It is assumed that mechanical completion of the WTG is conducted following the installation operations outlined above, and thereafter the electric commissioning work.

It is assumed that the WTG components are pre-transported from the fabrication site to a nearby port, prior to loading onboard the vessel. WTG installation requires a jack-up installation vessel, which places its legs on the seabed and jack-ups the vessel hull, providing a fixed platform onto which the WTG can be installed from.

In this case study, it has been proposed that the 10MW WTG is installed (Fig. 2.9-10) by a jack-up installation vessel (Fig. 2.12B) with four lifts. The components of the WTG are:

- Lower tower: 55m * 8m dia, 280tons (Fig. 2.9A)
- Upper tower: 55m * 6m dia, 220tons
- Nacelle:19m * 6m * 7m, 700tons (Fig. 2.10A and Fig. 2.11A)
- Rotor: 200m, 190tons (3 blades and hub assembled on the vessel) (Fig. 2.10B-C)

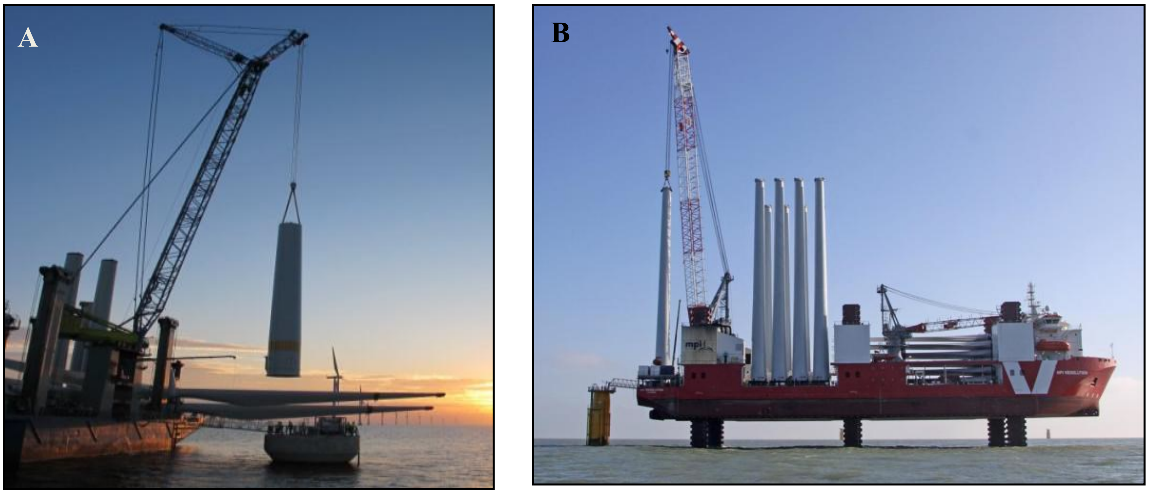


**Figure 2.9** Tower installation with: two lifts of a two part tower (**A**) and one lift of a single tower (**B**)

**Figure 2.10** Lift of the nacelle with a generator (**A**). Assembled rotor on-board the vessel (**B**) and lifting of the rotor with the blades pre-attached (**C**)

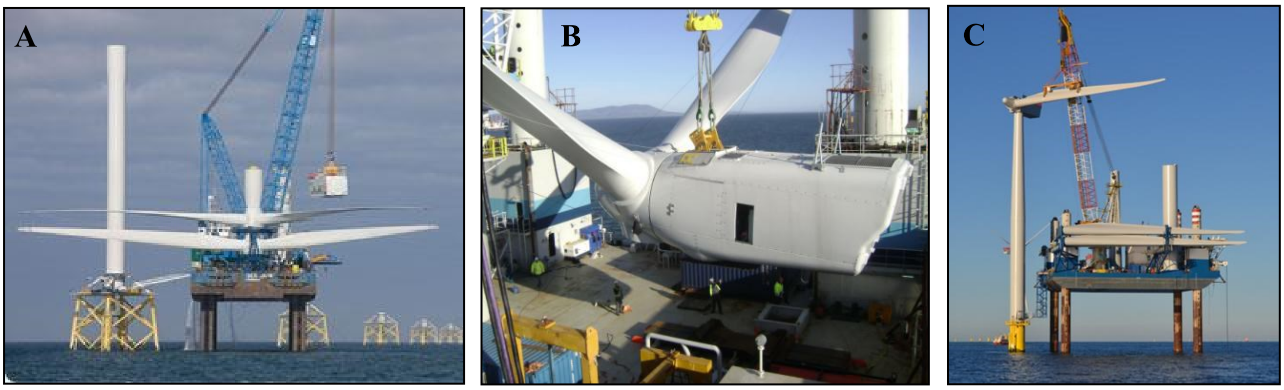


**Figure 2.11** Lifting the nacelle on top of the tower before rotor installation (**A**); Bunny-ear installation method (**B**); One-by-one blade installation (**C**)

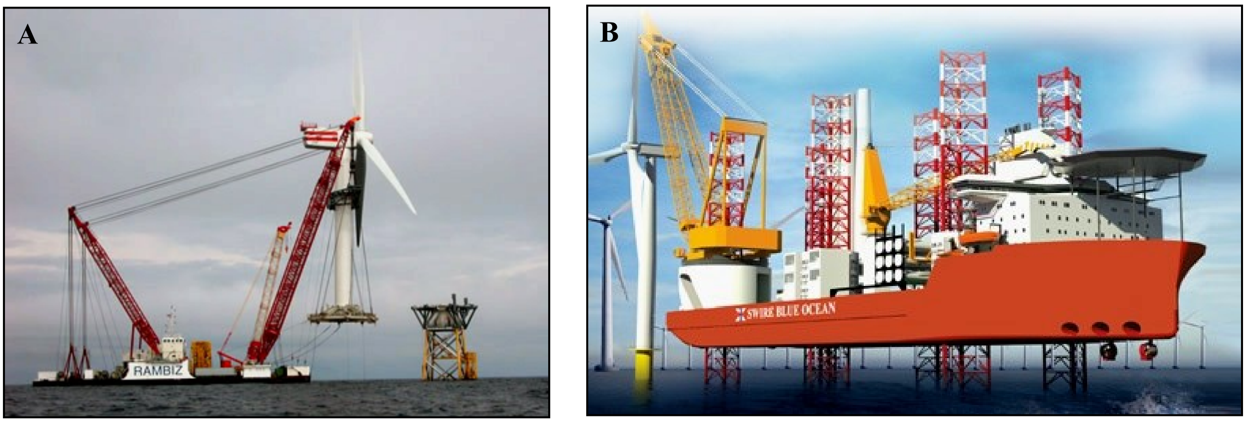


**Figure 2.12** Installation of a WTG as a single unit (**A**) and a high loading capacity jack-up installation vessel (**B**)

Other installation methods used in OWFs are the bunny ear method (Fig. 2.11B), then One-by-One blade method (Fig. 2.11C) and the single unit methods (Fig. 2.12A).

### 2.5.8 Substation installation

The substation installation has the following phases:

**a)** Float-out of self-installing substation platform from the dock.

**b)** Tow platform to offshore site using anchor handling tugs.

**c)** Position platform and start self-installing operation.

**d)** Land platform legs on seabed and install using suction bucket technology.

**e)** Elevate platform to predetermined height.

**f)** End of installation operations and demobilise vessels.

It is assumed that the platform is towed directly from the fabrication yard. The two sequential operations of a substation installation: substructure and platform installations are shown in Figure 2.13.

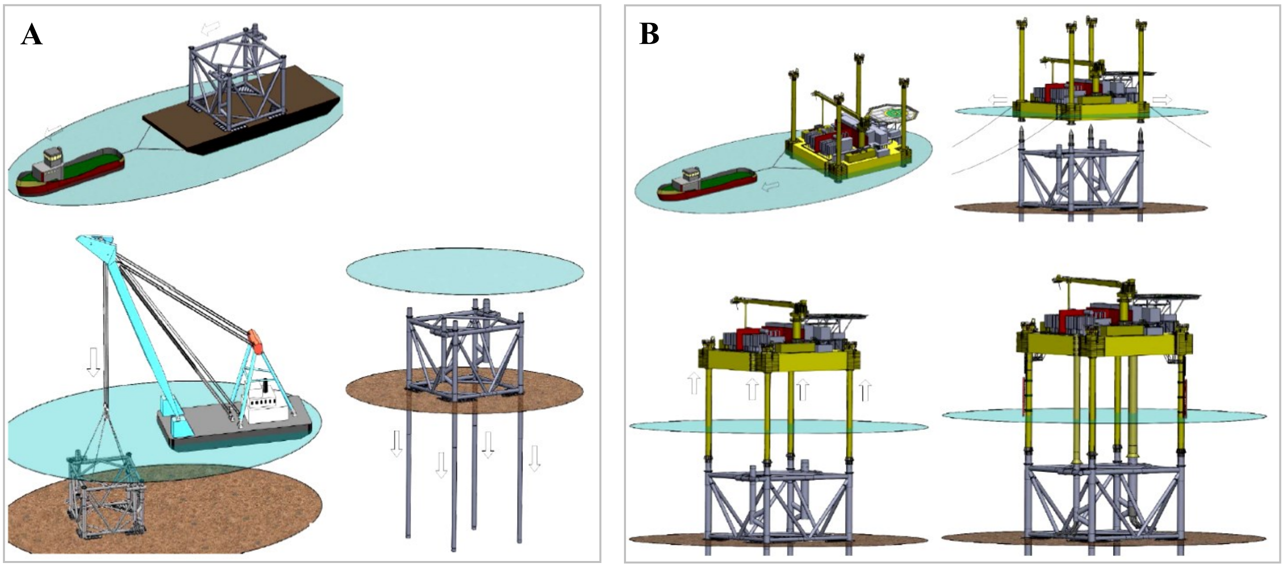


**Figure 2.13** Substation installations of the substructure (**A**) and the platform (**B**)

### 2.5.9 Cable installations

The plan for cable installations is composed of the following stages:

- **a)** Pre-lay grapnel along the planed cable route.
- **b)** Route clearance and pre-construction survey.
- **c)** Mobilisation of a cable lay barge.
- **d)** Loading on-board export cables in a nearby port.
- **e)** Installation of export cable between onshore substation and offshore substation starting with shore landing.
- **f)** Cover cables by trenching where possible, if not then rock dumping.
- **g)** Mobilisation of vessel for infield cables.
- **h)** Pickup of cables from factory and transport to site.
- **i)** Installation of infield cables from the substation to the WTGs.
- **j)** Cover cables by trenching where possible, if not then rock dumping.
- **k)** Demobilise vessels in port.

It is assumed that the cables are loaded on-board the installation vessel directly from the cable factory. The array cables are relatively short, e.g. between two WTGs it is 1.6km and between WTGs and substation it is 2 to 10km. The two power export cables are more than 100km and the installation will be a challenge. The major operation of the cable installation will be: cable laying and burial of cable. Figure 2.15 gives an illustration of the cable installation and Figure 2.14 shows a cable installation barge with a turntable.

**Figure 2.14** Cable installation barge with turntable.

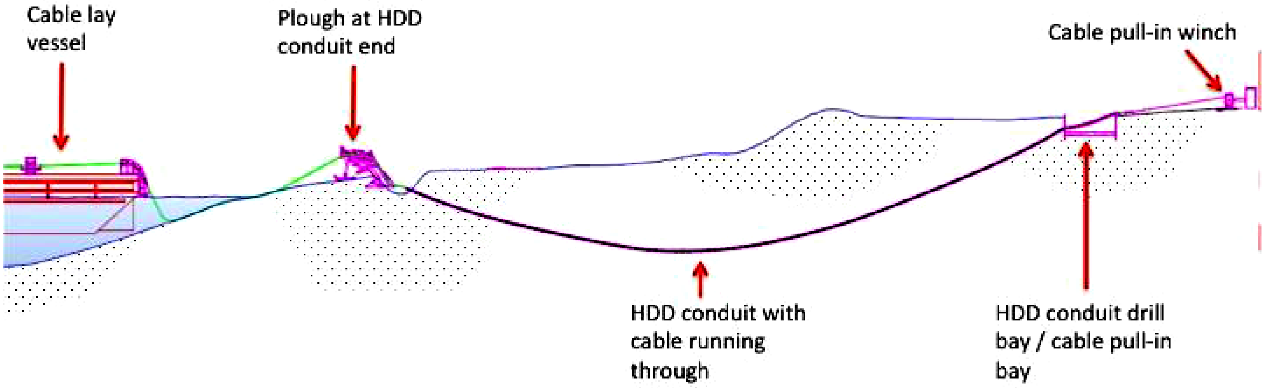


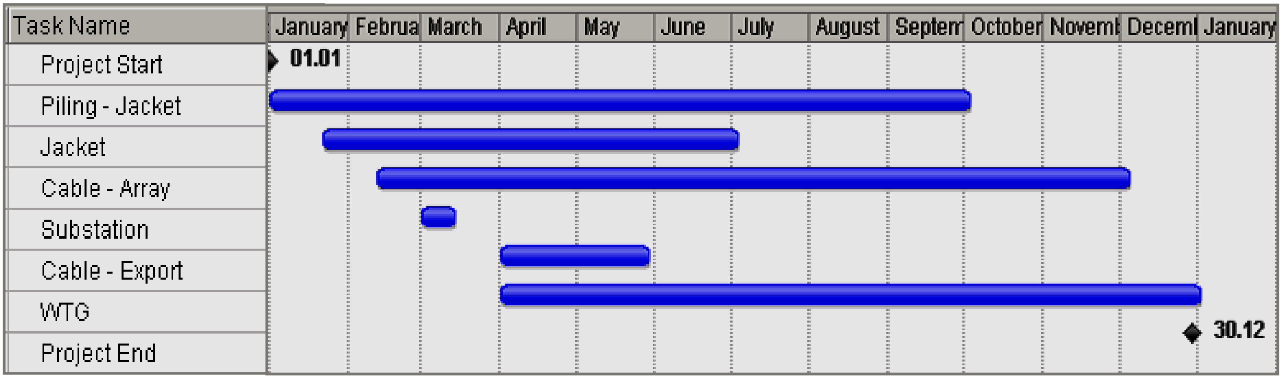
**Figure 2.15** Illustration of cable installation operations

## 2.6 Time Schedule for Installation Operations of Wind Farm

The installation period of Statoil's 318MW Sheringham Shoal OWF (88 units of 3.6MW WTGs) in the UK was more than two years. It commenced in June 2010 and finished late 2012. On a busy day at the Sheringham Shoal site, 32 vessels and 560 people worked there, which resulted in a high cost operation.

Shortening the installation period is crucial for OWF cost reduction and for minimizing environmental impacts. The goal of this MUP case study is to finish the installation period of a 1000MW OWF in one year. Several of the installation operations can run parallel with each other. The Table below summarizes all the total duration of each installation stage, including contingency (Table 2.5).

**Table 2.5** Total duration of each installation stage of a complete OWF



## 2.7 Installation of Aquaculture Farms

### 2.7.1 Fish cages

The components of the aquaculture farm have a much smaller weight and dimensions compared to the component of the OWF. The installation of a group of eight fish cages (circular: circumference 120m, depth 25m) is assumed to be take a one-month offshore work duration.

A group of 8 fish cages has a weight of 8 * 46tons and the mooring system a weight of 75tons. The fish cages will be assembled onshore (Fig. 2.17A) and towed complete to the offshore site. The offshore cage mooring (Fig. 2.16B) needs a work boat with a deck area of 6 x 10m$^2$ and a crane lifting capacity of 6tons. The personnel needed is between four to five crew members plus two divers. Figure 2.17B demonstrates the fish farm in operation offshore and Figure 2.17C displays next generation strong off-shore fish cages.

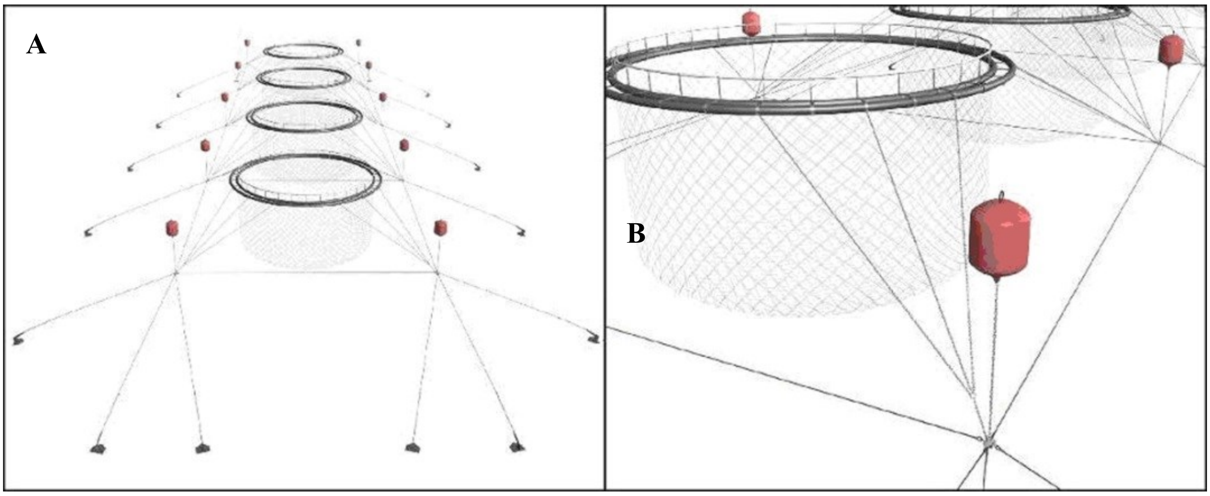


**Figure 2.16** Three dimensional illustration of the fish cage arrangement (**A**), including the mooring system (**B**)

**Figure 2.17** Fish cage assemble onshore (**A**); Fish cage operation offshore (**B**); and next generation strong fish cage (**C**)

### 2.7.2 Mussel production systems

Mussel production is assumed to use 20m production lines (drops). It can be submerged (5-7m below mean sea level) during storms to avoid mussel loss. The mussel production system is demonstrated in Figure 2.18.

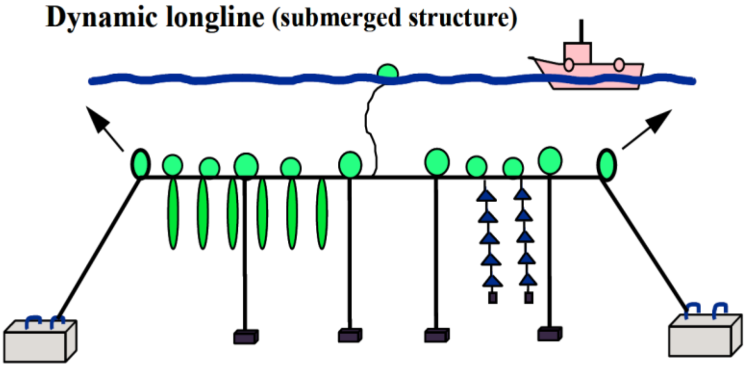


**Figure 2.18** Illustration of a typical mussel production line system

### 2.7.3 Seaweed cultivation systems

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) and convert it to marine proteins. The seaweed production system, besides its potential to absorb fish waste, it also attenuates waves. The installation period of a seaweed cultivation system unit (10m width and 100m long) with seven H structures (Fig. 2.20 [4]), takes approximately 12 hours and requires the use of a boat (Fig. 2.19 [4]).

**Figure 2.19** Installation of the seaweed cultivation system

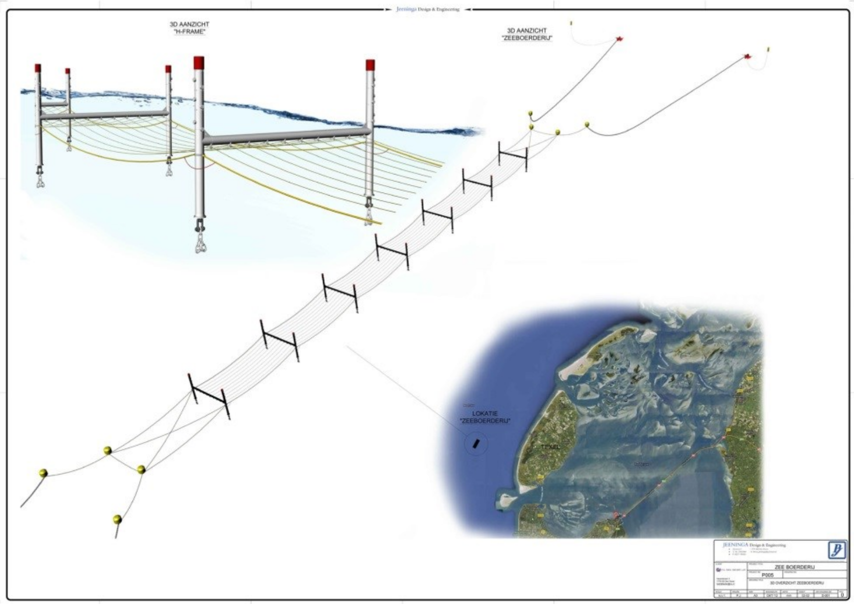


**Figure 2.20** H structure units of a seaweed cultivation system

## 2.8 Operation and Maintenance of 1000MW Offshore Wind Farm

### 2.8.1 Introduction

O&M vessels known as Wind Farm Service Vessels (WFSV) are utilized to bring personnel and handheld equipment/tools onboard the WTGs, in order to conduct maintenance and repair work; mainly on the WTG's and the substations. The most common way to access the OWF is to use crew transfer vessels sailing from shore to the WTGs during daytime. The literature review of WFSVs is presented in Appendix F.

There are various methods for entering a WTG; the most used method today is to push the vessel against the foundation (Fig. 2.21), whereupon the crew walk across a gangway and climb up the ladder to the main platform. This is an area in need of innovation, since the current method is not efficient or safe enough for the crew in harsh weather conditions. Heave compensated gangways have been introduced to ease the access from the vessel to the foundations.

**Figure 2.21** Current push-vessel-against-foundation method for assessing WTGs

For O&M requiring larger equipment (lifts, jack-ups, PSVs, etc.) for the repair of generators, blades, etc., larger specialized vessels are needed; since it is expected that OWF will increase in number and size in the future. Current WFSVs are generally less than 24m long, therefore generally coded to Maritime and

Coastguard Agency Cat 2, restricting operation to 60nmi from a safe haven. The regulations for ships greater than 24m are more onerous and stipulate additional safety features, however they can operate at a greater distance from a safe haven, which will suit a future OWF.

Seasickness and the associated fatigue with transit to the wind farm site, as well as any impact stress from a high speed catamaran, are major issues facing WFSV design. Fatigue levels need to be managed as journeys duration increases.

The MERMAID project's a case study of a 1000MW OWF comprising of 100 units of 10MW WTGs with two substations, is a future scenario of what MUP might be comprised of. O&M for such a large site, 100km from shore, requires careful planning.

A challenge for the WFSV industry is providing the right solutions for the future. When examining the OWF case study for the MERMAID project, the right solution for a WFSV is specific to the project's location, for example Sheringham Shore was constructed on a tidal site and that created site specific problems. For this reason designs are constantly evolving and continually changing with the requirements and expectations of OWF operators. WFSV designs are now evolving to meet the needs required for each vessel e.g. fast, comfortable, manoeuvrable at low speed, or stable at low speed, etc. These options must be considered in the design as they are not always compatible with each other. Examining the cost of a WFSV versus the day rate it will earn, affects design and what a WFSV operator can provide a client [10, 12].

### 2.8.2 Vessels for operation and maintenance

The transport between the O&M base and the individual WTG takes place with the use of a WFSV (Fig. 2.22). To gain an insight into the amount of these vessels in use one can look at the 4C Offshore Ltd website, which has 434 WFSVs listed in their database (http://www.4coffshore.com). The vast majority of these vessels are high speed catamarans with a cruising speed for 15-25knots and are generally between 15-24m in length. WFSVs can usually carry a cargo in the range of 3-15ton. Typically they are aluminium, though glass reinforced plastic and other composites have been used. The aim is to get to the wind farm a quickly as possible, whilst keeping seasickness and fatigue at a minimum. Most of these vessels use the industry standard method of bow transfers, using a reinforced bow with a rubber fender; a relatively large bollard pull allows the connection to be maintained safely, for most wave spectrums with a Hs of 1.5m. Other vessel types currently utilised for the WFSV industry include mono-hulls and SWATHs [10, 11, 12].

**Figure 2.22** M/S Elisabeth M, Monohull Offshore Wind Crew Vessel, KEM Offshore ApS, Denmark.

### 2.8.3 Time utilization for O&M work

For the MERMAID case study of a 1000MW OWF comprising of 100 units of 10MW WTGs with two substations, the following assumptions are made;

- Planned maintenance has a duration of 4 days, for 2 persons per WTG, per year.
- Un-planned maintenance is 4 days, for 2 persons per WTG, per year.
- Maintenance of one substation and the related cables is assumed to be equivalent to 10 units of WTG, thus: 80 days, for 2 persons, per year.

Accordingly, the O&M work requirements for the 1000MW project is 1760 person-days per year.

In the following discussion of O&M access, tables of representative data for the North Sea site can be found (Table 2.6). A more detailed breakdown of the Sheringham Shoal Offshore Wind Farm 2002 data can be found in Appendix G.

If O&M work can be carried out 24 hours per day, the service vessel accessibility is given in Table 2.6. The percentage accessibility is calculated from the ratio of the number of weather window hours to number of hours per year. This is similar to existing carried out studies [13, 14].

**Table 2.6** Representative data of O&M access at the North Sea Site

| Significant Wave Height, $H_s$ (m) | No. of Weather Windows | % Accessibility |
|---|---|---|
| **1** | 426 | 39 |
| **1.5** | 660 | 60 |
| **2** | 800 | 73 |
| **2.5** | 903 | 82 |
| **3** | 976 | 89 |

However, if O&M is carried out between 6am and 12 midday then the number of weather windows reduce to those shown in Table 2.7. The percentage accessibility is now calculated from the ratio of number of working days, to number of days per year. Generally, operations are planned to avoid night working hours, therefore trips after 12 midday maybe not utilized. This restricts the number of working days to those tabulated below. Consequently, the percentage total accessibility is significantly reduced, due to only one trip carried out per day and not using late hours. For further details on the assessment of weather windows see Appendix H.

**Table 2.7** Number of Weather Windows for a North Sea Site (day beginning 6:00 – 12:00)

| Significant Wave Height, | Working Days | % Days Worked | % Total Accessibility |
|---|---|---|---|
| **1** | 140 | 38 | 13 |
| **1.5** | 228 | 62 | 21 |
| **2** | 273 | 75 | 25 |
| **2.5** | 313 | 86 | 28 |
| **3** | 330 | 90 | 30 |

## 2.9 Fish Farm Operation

The production of fish and the O&M of the marine fish farm includes the entire lifecycle of the fish from spawning and breeding on land to its transfer to the sea, culture to commercial size, harvest and transfer back to shore (Fig. 2.23). Operations include feeding, medical treatment (when needed), biofouling net cleaning and if needed fallowing. The total approximate production cycle of salmon takes approximately 10-16 months in freshwater, plus 14-24 months in sea water – in total 24-40 months.

Because of the recommendation to use smolts greater 400gr. to seawater transfer at the North Sea site, the production cycle period in freshwater will be extended by approximately 8 months, while the period in seawater will be shortened by approximately 8 months; compared to the production cycle undertaken in for example Norway.

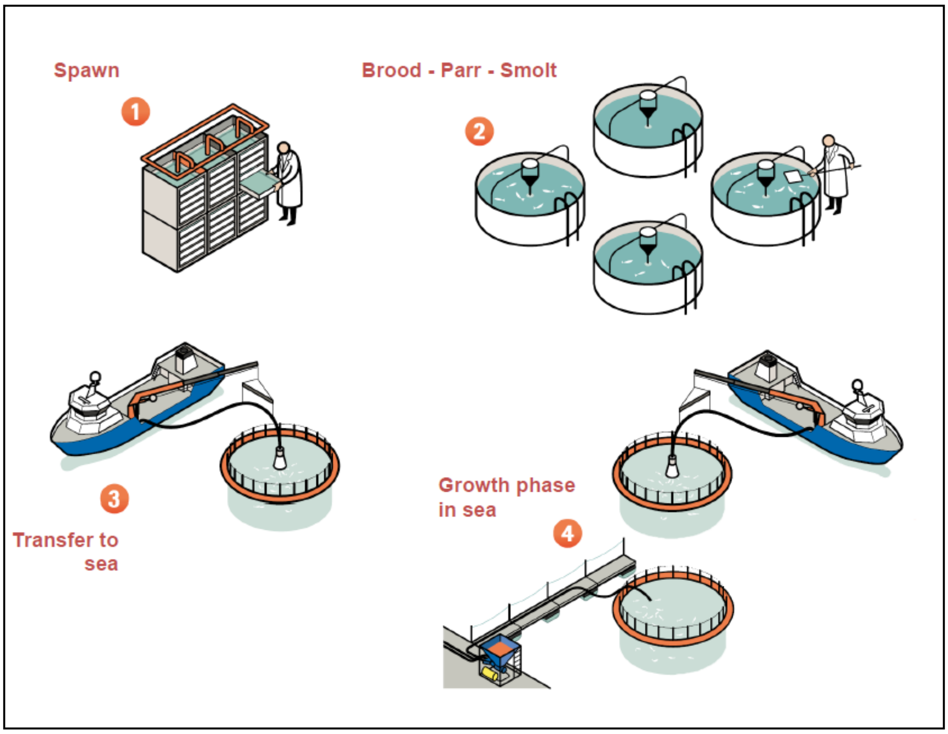


**Figure 2.23** Conceptual diagram of aquacultured fish lifecycle processing [15]

The operation of the fish farm at the North Sea site will include activities around the clock all year round. Smolts will be preferably transferred to seawater in late winter/early spring, when temperatures are acceptable and the risk of winter storms is less. From the time of transfer to seawater to harvest of fish, the main activities at the farm are feeding and fish welfare monitoring.

The main aspects of daily, weekly and periodical O&M of a fish farm are listed as follows:

Operations and maintenance (daily)

- Feeding. This is performed and controlled from the feed barge. Software systems are used to follow up on the amount of feed required (at each life-cycle stage and season) and the growth of fish.
- Monitoring of feeding behaviour to control intake amount by fish. This is done mainly with use of a camera that can be move up and down inside the net cage and is controlled from the feed barge control room.

- Removal of dead fish. It is a requirement by law that all cages are checked daily for any dead fish and that any dead fish are removed.
- Visual control of all equipment and units to be in working condition.

Operations and maintenance (weekly)

- Refilling of feed storage tanks on the feed barge from special feed vessels.
- Sampling of fish to determine size and weight, to monitor health conditions and to count sea lice infections.

Operations and maintenance (periodic)

- Receive smolt (juvenile salmon). Arrival by specialized well boats.
- Change of net cages. The net needs to be changed at least once during a production cycle. At the start when fish is small, a smaller net opening is used and it must later be changed to a larger, deeper net with larger openings, when fish grow in size. This allows better in-flow of water in a cage.
- Cleaning of nets to remove and prevent bio-fouling. Coastally it can be as frequent as every week but in off-shore water, it is expected to be less frequent.
- Medical treatments to remove sea lice and possibly other parasites from salmon.
- Deliver marketable-size fish to a well boat for transport to harvesting and processing facility (Fig. 2.24D).
- Fallowing of the site for at least two months every two year.

Different types of vessels are necessary for the O&M of an off-shore fish farm (Fig. 2.24).

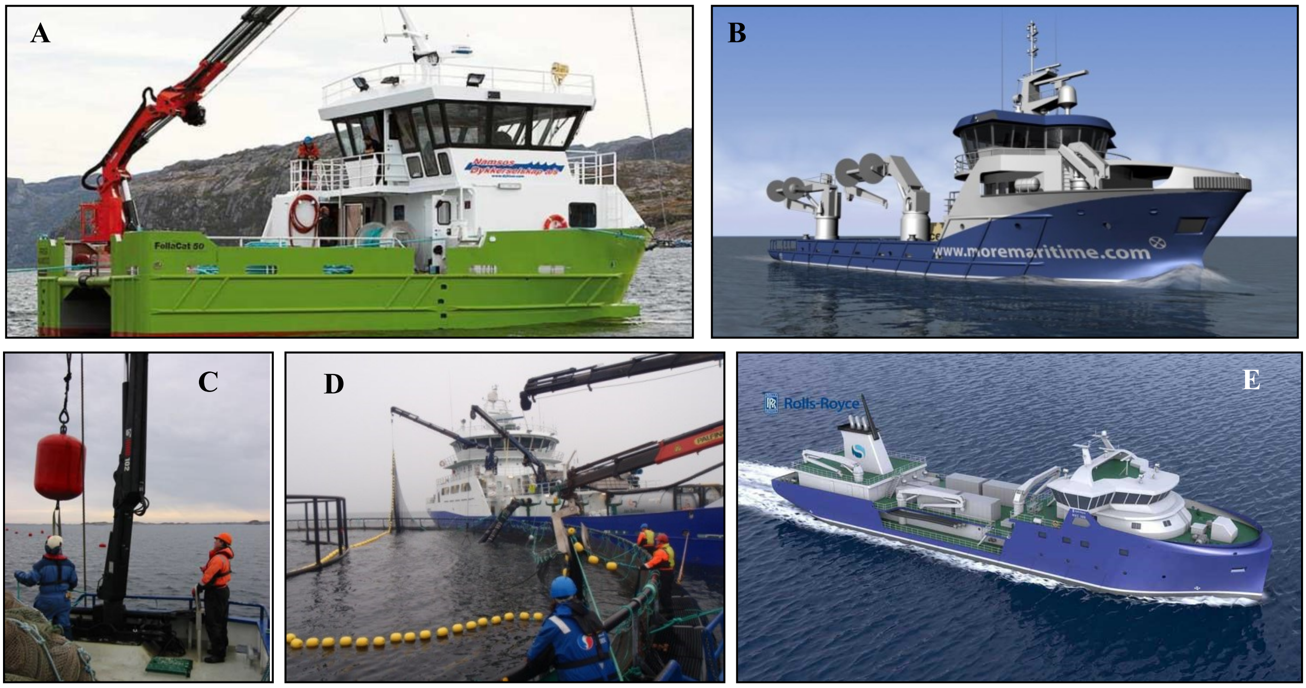


**Figure 2.24** Fish farm service vessel (**A**); Møre Maritime's next generation supply vessel (**B**); Fish farm service vessel operation (**C**); Live fish pumped into a well boat (**D**); 2013 Ronja Polaris with a 3000m³ volume capacity (**E**)

## 2.10 Brief discussions of MUP with wave energy

### 2.10.1 Introduction

This section will qualitatively discuss the potential integration of Wave Energy Converters (WECs) into the proposed MUP layout (Fig. 2.2). The focus of this report has been on a wind and aquaculture combination, wave energy integration will be briefly discussed in this section.

The integration of WECs will be with the proposed MUP layout presented above: 1000MW offshore wind (100 units of 10MW WTG) production combined with 16 fish-cage, 8 mussel and 18 seaweed production units.

The brief discussion of WEC inclusion has the following five aspects:

- Types of WECs
- The ratio of wind energy to wave energy
- The layout of the proposed MUP with WECs
- The installation of WECs
- The operation and maintenance of WECs

### 2.10.2 Types of the Wave Energy Converters

Three types of the WECs will be illustrated in this section as examples. In MERMAID work package 3, further types of WECs are considered and may also be used as a basis for the design of the MUPs.

The first WEC considered is the Wave Star (bottom fixed type) (Fig. 2.25A) [6]). This concept consists of a main body piled into the seabed with attached floaters. It is suitable for low to medium water depth. Typical size of the structure is 70-100m long with 20 floaters. Capacity per unit is 0.5-2 MW [6]). The second WEC considered is the Pelamis (Floating Attenuator) (Fig. 2.25B). The floating body unit is around 180m long, with a capacity of about 0.75-1MW. It suits water depths above 50m [7].

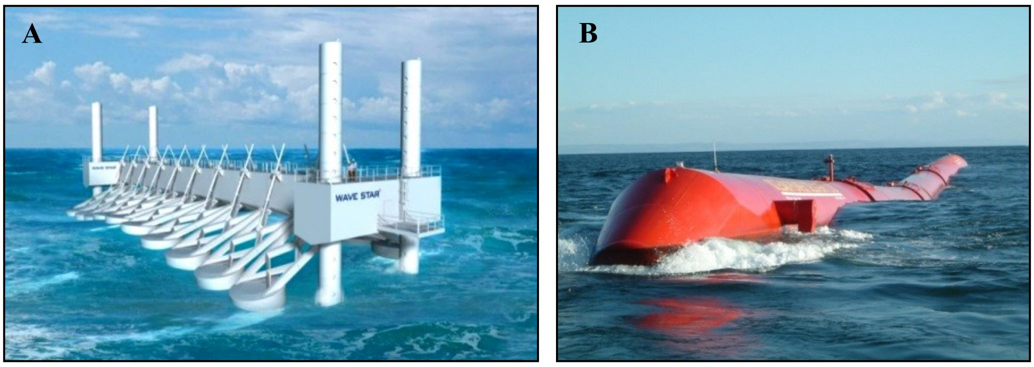


**Figure 2.25** WECs: Bottom fixed Wave Star [6]) (**A**) and the floating Pelamis [7]) (**B**)

Lastly, the third WEC is the Floating Power Plant's device (Fig. 2.26). The floating platform presents a combined wind/wave concept. There are different sizes and configurations for testing and the P80 version is equipped with 2.3MW WTG and a number of floaters with a total wave-capacity of 1.6MW [8].

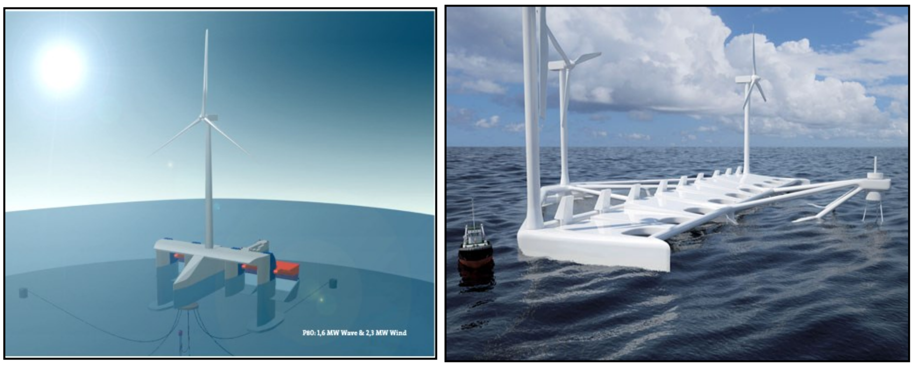


**Figure 2.26** Illustrations of the two configurations of the Poseidon floating platform with a combined wind/wave concept (source and ownership: [8])

### 2.10.3 The layout of the proposed MUP with Wave Energy Converters

The proposed layout of the MUP with WECs is shown in Figure 2.27. Twenty four groups of the wave units are proposed to be located at the boundary of the wind farm and 15 groups to be located inside the wind farm. The location of the wave should avoid the conflicts both with the OWF and with the aquaculture. The vessels should have access to both offshore wind and aquaculture farm easily. In addition, the seaweed shielding on the wave converter units should be also considered. Each wave energy converter group can be one or several wave energy converter units.

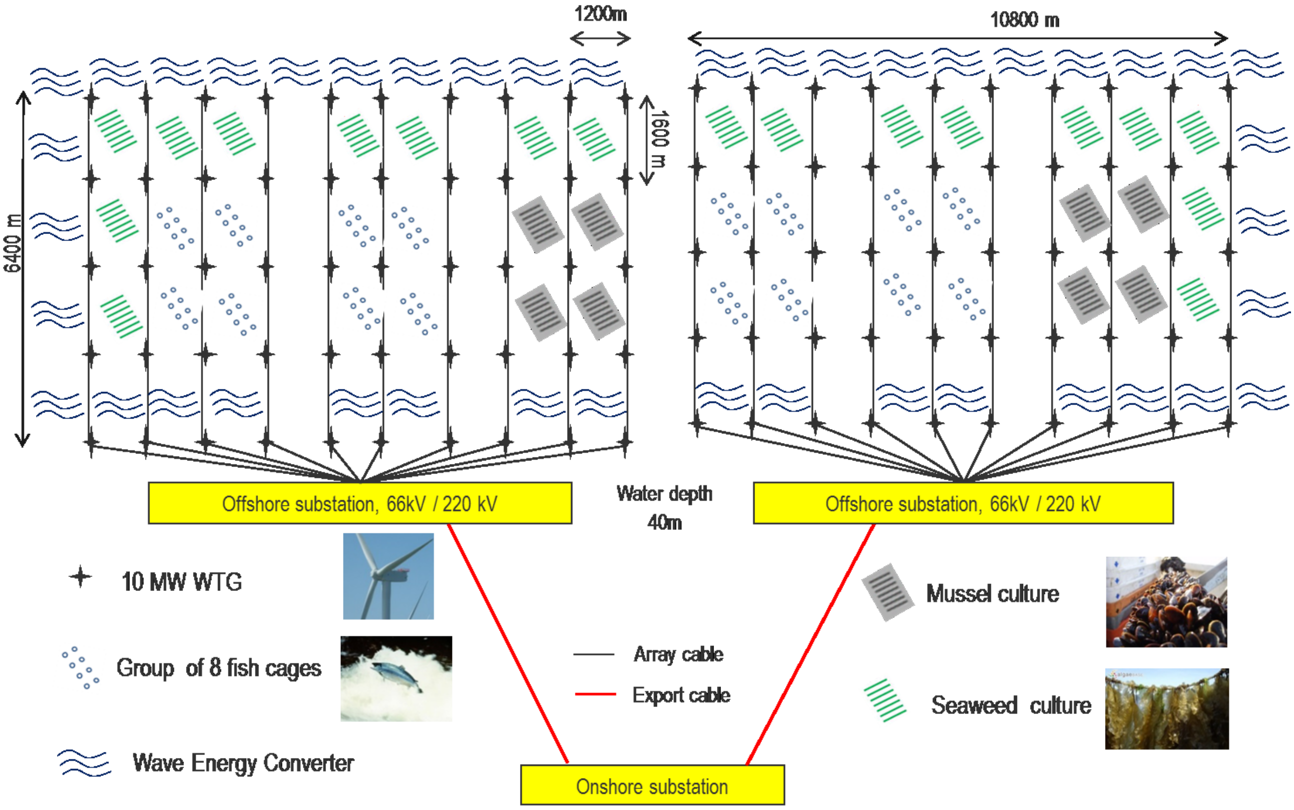


**Figure 2.27** MUP layout of integrated wind, aquaculture and wave farms.

### 2.10.4 The ratio of wind energy to wave energy

A combined wind and wave power installation will increase the total power yield (Fig. 2.28). In addition, the combination has the potential to deliver more smooth output power. A lower wind and wave capacity ratio of 1 (100MW wind and 100MW wave) results in a more stable system output power than a higher wind and wave ratio of 10 (1000MW wind and 100MW wave) (Fig. 2.29). The wind and wave energy integration has the potential to give a more stable power output than for the wind farm alone; however, further investigations are required [3]. The figures below show some simple simulation examples.

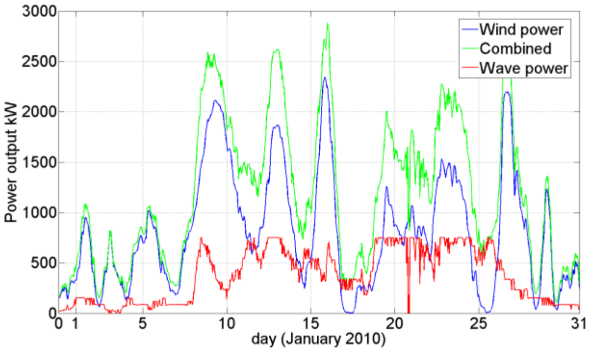


**Figure 2.28** Power output from WTG, WEC and combined

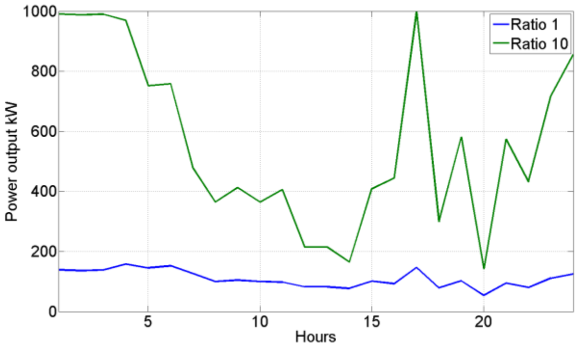


**Figure 2.29** Ratio: wind / wave power capacity

### 2.10.5 The installation of wave energy converter

Installation of the WECs have a number of similarities to installation of the WTGs but also some different steps and operations. For bottom-fixed devices like the Wave-Star unit, different installation strategies exist. One way would be to have an initial piling operation, followed by installation of the topside. A piling operation could easily be done similar to piling of the jackets for the wind farm; however, another piling template would be necessary. Installation of the topside will require a larger vessel depending on the actual weight of the topside. If so, only limited synergies will exist with the WTG installation process for this particular operation.

Floating wave units are usually installed by a towing operation, where the platform is preassembled in a harbour and towed to site. Towing vessels are generally available and relatively cheap to hire. Similar vessels may also be required for installation of some aquaculture systems. However since the distance to shore is over 100km, it may be a quite complicated operation to install the required number of units. Towing speed is usually slow and weather dependent.

The installation of WECs will be a challenge due to the heavy lifts and long towing route. Only limited synergies exist between the WTG and the WEC installations.

### 2.10.6 The Operation and Maintenance of Wave Energy Converters

Normal O&M for WTGs will be by boat or in certain cases by helicopter. Similar for aquaculture, some kind of boat access is needed.

For the bottom-fixed WECs or the large floating platforms, access by boat for O&M on-site will also be possible. For the platform type, a shielded "harbour" may be provided on the back-side, leading to increased access possibilities. The Pelamis-type floating unit requires a towing operation to harbour-site, which will involve long sailing times and extended periods of non-availability for power production. It will be a challenge to find a suitable logistical setup due to the long distance from shore.

In general, service by helicopter may be preferred, especially for unscheduled maintenance, due to the large distance to shore and harbour. The examples of wave devices, except for the Pelamis-type, will be suitable for service by helicopter, either by hoisting or landing on the structure.

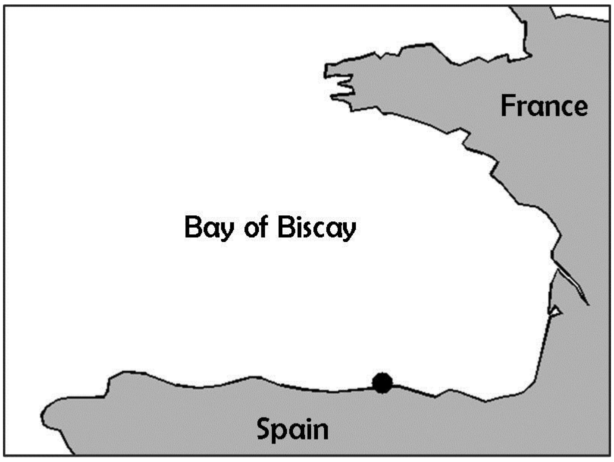
For the yearly scheduled maintenance it could be an advantage to have people living on-site. The wave-devices could be suitable structures for such housing facilities and also provide other services, eg. for the aquaculture farm.

# 3 The Atlantic Sea Site MUP case study

Please note that this MUP is not project-specific though it is based on the deep water conditions at Atlantic site. The goal of this case is to briefly discuss the different installation technology of the floating wind turbine. The MUP project-specific case will be given in the deliverable from WP7.

## 3.1 Characteristics of the Site

The Atlantic site is located in the Bay of Biscay (Fig. 3.1). The site is characterized by water depths greater than 100m and it is an area of heavy swells, winter storms and a high tidal range. Salinity is between 34 and 36°/°°and in the period from 2000-2013 surface water temperature (0-10m) ranged from 11 to 23°C with an annual average of 16.7°C [9].



| | |
|---|---|
| Sea | Atlantic Sea |
| Country | España |
| Site name | COS |
| Latitude | 43°34'12" N |
| Longitude | 3°51'32" W |

**Figure 3.1** Location and geographical coordinates of the Atlantic site

## 3.2 Layout of MUP

At the Atlantic sea site, the floating WTG concept will be considered. Mainly two types of floating WTGs have been successfully in operation, they are Hywind (spar) of 2.3MW (Fig. 3.2A) and WindFloat (semi-submersible) of 2MW (Fig. 3.2B).

A prototype of the WindFloat system, equipped with a Vestas v80 2.0MW turbine, has been operating successfully off the coast of Portugal since October 2011. This was the first multi-megawatt offshore WTG to be installed without the use of any heavy lift vessels. Additionally, no pilings or seabed foundations were required. All final assembly, installation and pre-commissioning of the WindFloat (including hull and turbine) took place on land in a shipyard's dry-dock. The complete system was then towed offshore using conventional tug vessels shown in Figure 3.3. The installation procedure was as follows: Floating Foundation → Lifting Tower → Nacelle → Blades.

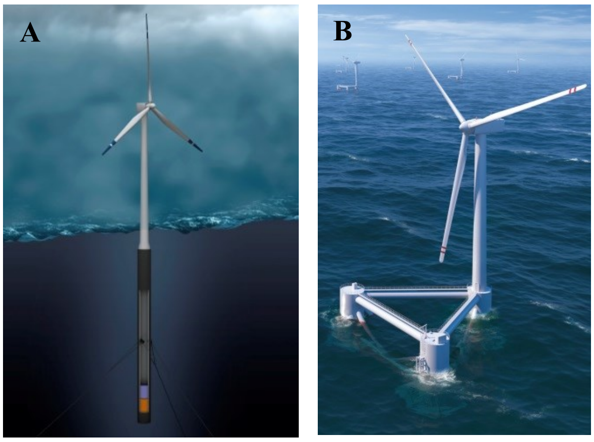


**Figure 3.2** WTGs Hywind (**A**) and WindFloat (**B**)

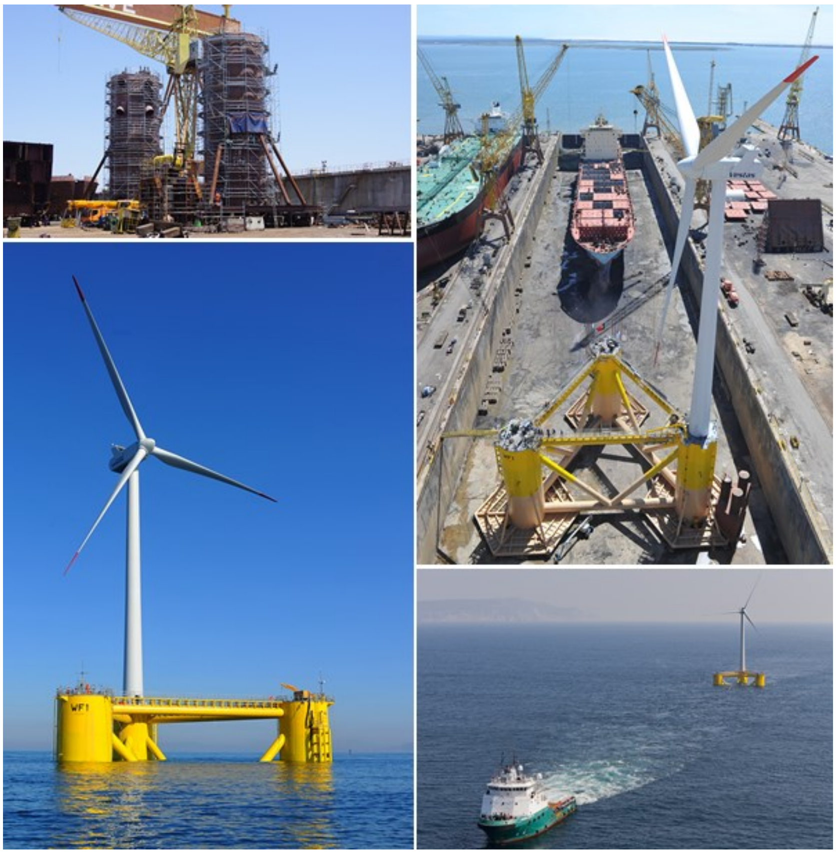


**Figure 3.3** WindFloat on-shore commissioning and offshore towing as one unit

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 Figure 3.4.

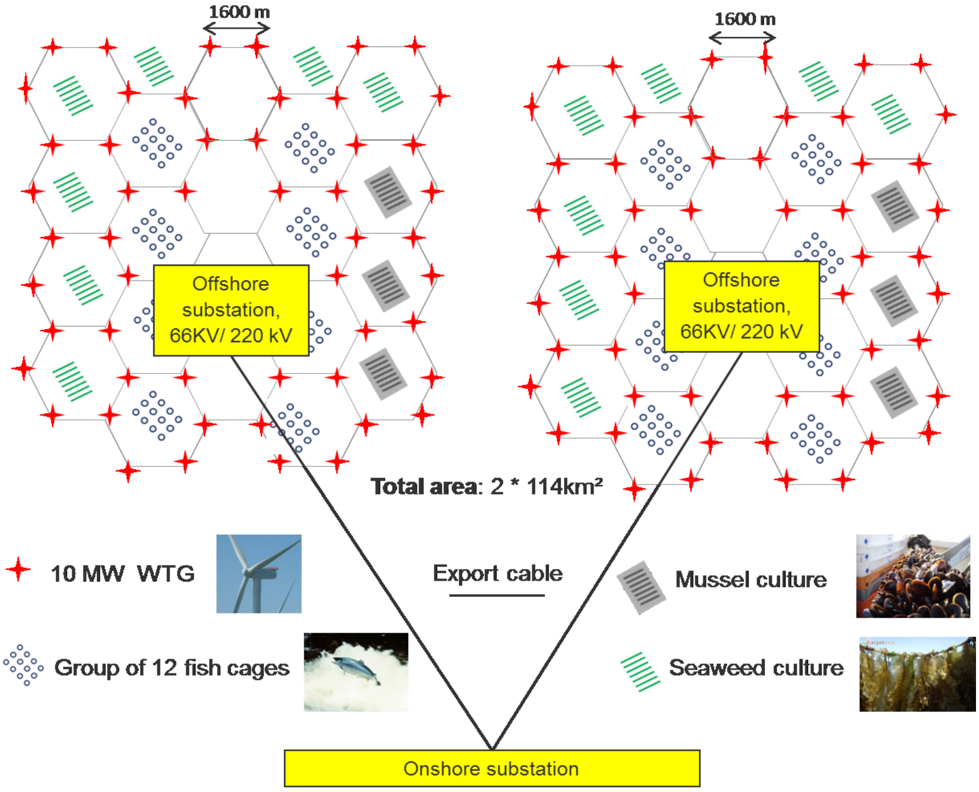


**Figure 3.4** Layout of 100 units of 10MW floating offshore wind turbine generators with aquaculture farms

### 3.3 Estimates of the Potential Production Rates and Yields

The estimation of the production rates and yields of the 1000MW wind farm integration with aquaculture (as shown in Fig. 3.4) is given in Table 3.1. 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 6 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 3.1** The MUP potential annual production rates and yields

| | Annual production | Annual yield | Comments |
|---|---|---|---|
| **Electricity** | 3 300 GW/h | 471 M€<br>(0.14 €/kWh$^{-1}$) | |
| **European sea bass** | 90-105 000 tons | 360 to 420 M€<br>(4 €/kg) | Amounts to 76-89% of the electricity yield! |
| **Mussel** | 23-34 000 tons | 23-34 M€<br>(1 €/kg) | |
| **Seaweed**<br>(e.g. sugar kelp) | 250-290 000 tons | 250-290 M€<br>(1 €/kg) | |

### 3.4 Transport and installation of Hywind at the Atlantic site

The components of a Hywind WTG are listed as follows:

- Mooring system
- Power cable
- Sub-structure
- Transition piece
- Tower sections
- Nacelle
- Rotor

#### 3.4.1 Mooring system

The mooring system for the Atlantic site WTGs is assumed to be the same type as the mooring system for Hywind Demo. The lower part of the mooring system (anchor and bottom chain segment) should be pre-installed, and all WTGs of the wind farm will share anchors with other WTGs. For the WTGs on the border of the wind farm it is not possible to share with more than one other WTG, but all other inner WTGs can share an anchor with two other WTGs.

Sharing anchors requires that they can be put down at a very specific position on the sea bed, therefore should be suction anchors or possibly freefall gravity anchors. Drag anchors, such as those used on Hywind Demo, are not suitable.

The rest of the mooring system (steel wire, possible clump weights, coupling chain and plates) can either be pre-installed together with the lower part, or it can be installed when the WTG is hooked up at the site (as was the case for Hywind Demo). If a pre-installed solution is selected, the steel wire must be kept away from the sea bed so that sand and small items do not come in between the steel fibers; thereby causing an increase in wear to the wire. This can be done by buoys, but it is a factor which makes marine operations offshore more complicated, and should probably be avoided in this case study site.

There are reliable manufacturers of mooring chains in the region of Cantabria (Vicinay), but the mooring system components can also be produced at other locations and shipped to the Atlantic site.

### 3.4.2 Power cable

The power cable route must be prepared by dumping rock and trenching (as for Hywind Demo).

Unless the power cable is buried deep into the sea bed, the decision on whether to install the power cable before or after the aquaculture devices depends upon the type of work and marine operations needed for installing the latter. The amount of operations in the area necessary for installing the aquaculture farm will be considerable, and the probability of unwanted interaction with a pre-installed power cable seems to be uncomfortably high. It is assumed that aquaculture equipment are relatively cheap structures which are relatively robust, so the probability and consequences of damaging some of them are not likely to be a problem. The power cable, however, should be put at minimum risk, and it is therefore proposed that it is installed after all other operations on the field related to the aquaculture farms have been terminated.

The power cable can be fabricated anywhere in the world, put on a reel and shipped to the Atlantic site.

### 3.4.3 HYWIND 10MW offshore Wind Turbine Generator

At present a 10MW WTG does not exist. The largest offshore WTGs which have been installed offshore are 6MW Siemens WTGs with a 120m rotor diameter (DONG's Gunfleet Sands). At DONG's Westermost Rough, 6MW Siemens with 154m rotor are under installation. Vestas have their 8MW 164m turbine undergoing onshore testing at Østerild Testcenter in Denmark. These are bottom-fixed WTGs.

The current largest floating WTG installed is Hywind Demo with its 2.3MW production, but it will not be long before significantly bigger floating turbines are installed. The Fukushima Floating Offshore Wind Farm Demonstration Project have published plans to install two 7MW floating WTGs before 2015. Statoil are working on a pilot park of floating WTGs off Scotland. The WTG size for Hywind Scotland will probably be in the range of 6MW or larger. Nevertheless, it is still quite a big leap up to 10MW. The dimensions of the turbines used for this study must be based on educated guessing using the data for the largest turbines of today. We shall use the same data as in the evaluations of the 100 * 10MW bottom-fixed wind farm for the North Sea site.

In this case study the following data were used:

- Hub height : 136m
- Rotor diameter : 208m
- Nacelle mass : 700tons
- Hub + rotor mass : 190tons
- Lower tower elevation : 26m

- Lower tower length : 55m
- Lower tower mass : 280tons
- Upper tower length : 55m
- Upper tower mass : 220tons

It is difficult to estimate the dimensions for the sub-structure without going into design detail. The substructure must be dimensioned and ballasted such as to provide the best possible dynamic properties for the entire WTG. This means that the natural periods for the different degrees of freedom must be carefully tuned relative to each other. Such a process is outside of the scope for this work, and the following non-designed dimensions and weights will be used for the sub-structure:

- Draft : 120m
- Diameter : 9m
- Mass (steel) : 1 280tons
- Mass (ballast) : 5 150tons

Two alternatives will be discussed in this study:

- three-bladed rotor
- two-bladed rotor

The reason for the two alternatives in rotor number is that the two-bladed rotor has for some attractive advantages with respect to installation.

Tower sections, nacelles and rotors for wind projects are manufactured by the project's WTG supplier (Vestas, Goldwind, United Power, Gamesa, Enercon, GE, Samsung, Siemens, REpower, etc.). This will also be the case for the 1000MW Atlantic site Hywind OWF. The strategy selected for transport, assembly and installation of the turbines will determine where the components should be transported for assembly. In this study two different strategies for vertical assembly will be discussed.

## 3.5 Transport and installation of 100 * 10MW three-bladed turbines

Three-bladed horizontal axis turbines are the most commonly used for on- and offshore wind developments.

If a vertical assembly strategy is to be used, the transport and assembly procedure will be very similar to that of Hywind Demo. 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 WTG supplier, transported to the assembly site and lifted onto the sub-structure in a number of lifting operations (typically four) (Fig. 3.5). Due to the deep draft of the sub-structure it is most likely that lifting operations must be done using a floating crane (unless a quay with more than 120m depth is available). Due to the large lifting heights, operations will be dependent on good weather. In the case of Hywind Demo, there were very strict limitations on wave height and period (with period being most critical). For a 10MW Hywind turbine, lifting height will be even larger (136m hub height + lifting arrangement) making weather limitations even more strict. In any case, use of very large and expensive crane vessels (S7000, Thialf, or similar) will be necessary. Additionally, operations would have to take place in sheltered waters, i.e. far from the Atlantic site, and then the fully assembled WTGs would have to be towed to the Atlantic site.

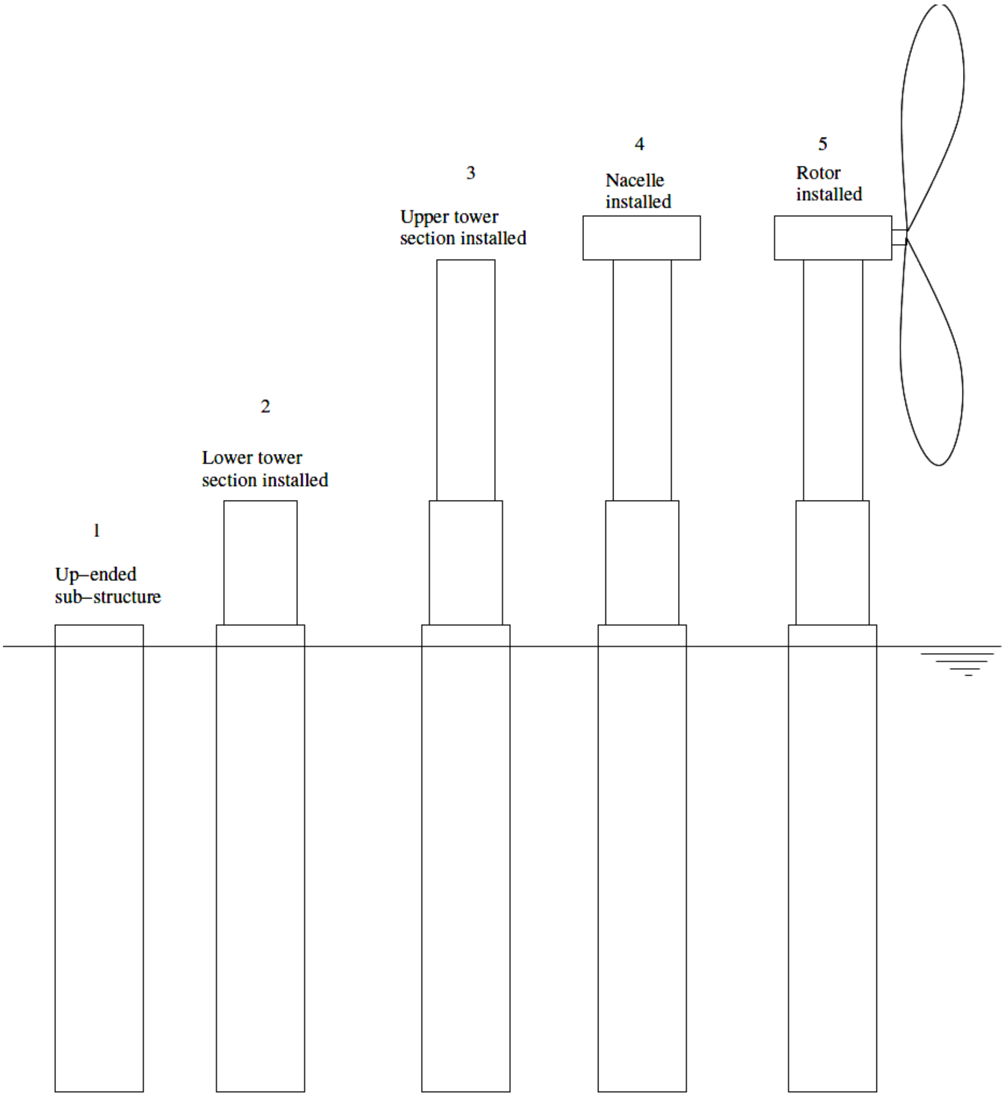


**Figure 3.5** Phases of vertical assembly procedure for three-bladed wind turbine generator.

### 3.5.1 Transport and installation of 100 * 10MW two-bladed turbines

Two-bladed WTGs are not yet used on offshore sites, and are not commonly used onshore either.

Condor Wind Energy Ltd (www.condorwind.com) has a 6.1MW two-bladed WTG, designed for offshore deployment. If more suppliers take on the challenges posed by this technology, it is not unrealistic to say that a 10MW two-bladed WTG can be developed within a similar timeframe as three-bladed WTGs are being developed.

A two-bladed WTG is slightly less effective than a three-bladed WTG, but this can be evened out by slightly increasing the rotor diameter. The blade chord, and therefore also the thickness, of two-bladed rotors is larger than for three-bladed rotors. A thick blade is stronger than a thin blade, and the use of structural material for two-bladed rotors is therefore lower than for three-bladed turbines.

The main challenge with two-bladed WTGs is their asymmetry. Three-bladed WTGs are symmetrical, and therefore easier to develop than two-bladed WTGs. The hub and blades in two-bladed rotors are hinged to the turbine shaft (teeter hub) in order to reduce the loading on the structure.

One advantage of two-bladed WTGs for offshore application is the huge potential they have in reducing complex marine operations. A two-bladed offshore WTG can be vertically assembled as shown in Figure 3.6. No high lifts are required. The nacelle and rotor can simply be floated over the upper tower segment and connected. Particular attention is needed for ballasting and load transfer, but this is a relatively simple operation involving pumps and hoses. The hull structure all the way up to the nacelle must be reinforced, so that it can withstand the water pressure. This will result in a structure which is stronger than necessary needed for normal operation, but the increase in material cost must of course be considered together with all other costs.

A water depth of at least 120m + 55m + 55m + 26m = 256m is necessary for this assembly method. This means that the components can be manufactured at suitable production yards around Europe, transported to Bilbao or Santander and then brought to an offshore assembly site off the Cantabria coast, with sufficient water depth for final assembly. After assembly, the WTGs can be towed to the (nearby) Atlantic site.

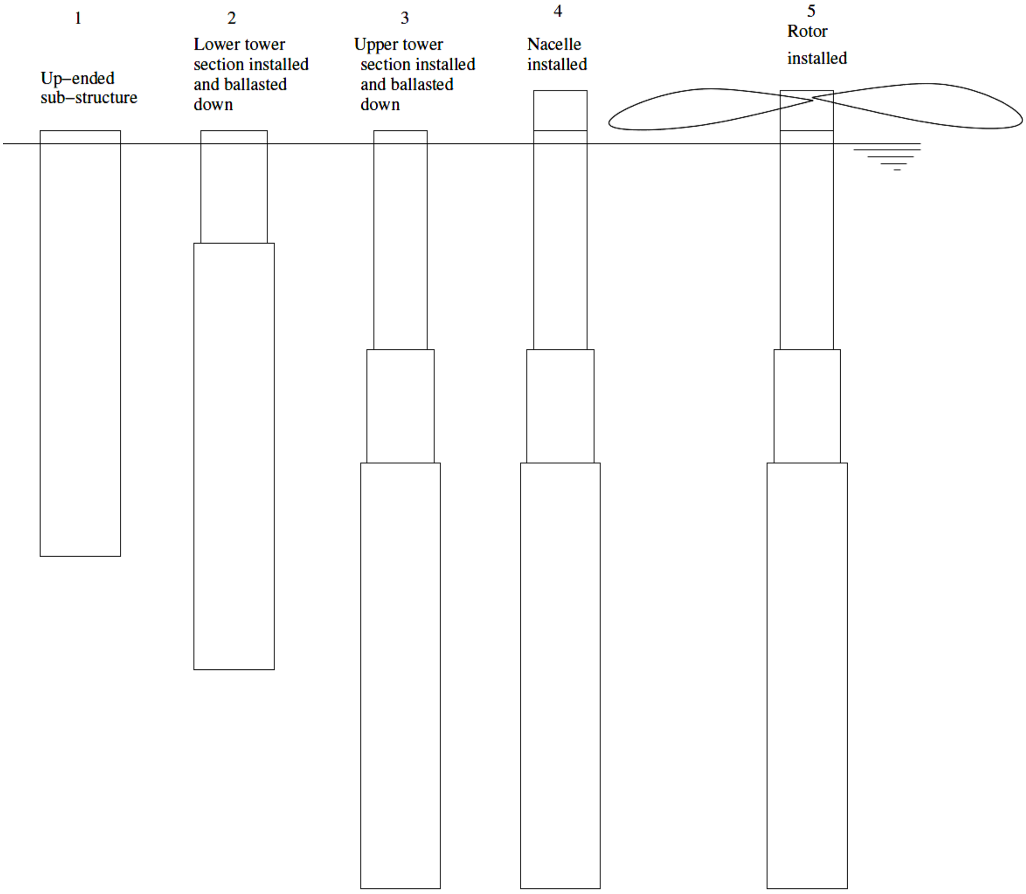


**Figure 3.6** Phases of vertical assembly procedure for two-bladed wind turbine generator.

## 3.6 Operation and Maintenance of Hywind at the Atlantic site

It is difficult to predict O&M requirements for a future 100 * 10MW OWF. As a reference, it will be interesting to look at the O&M activity at the Sheringham Shoal OWF in Great Britain. This wind farm consists of 88 WTGs 3.6MW each, located about 20km offshore. The number of WTGs and the distance from shore are considerably comparable to the wind farm under consideration for the Atlantic site. At Sheringham Shoal a total of four service vessels are hired. Three of these sail every day (on average), and a total of about 30 people are involved in the daily O&M activities (on average).

It is reasonable to assume that the WTG technology will develop so that less maintenance is needed in the future. At the very least, one should expect that the development of condition based maintenance and monitoring systems is developed to such a level, that the most severe failures and thereby the most costly unscheduled maintenance operations, can be kept at a minimum. The O&M differences between floating WTGs and WTGs with fixed foundation also need to be explored.

## 3.7 Brief discussion of the wave farms

In general, conditions at the Atlantic site are more favourable to wave energy than in the North Sea. The average wave potential is greater and the distance to shore on the proposed site is much less than in the North Sea case study. Due to the increased water depth, bottom-fixed structures are not suitable but floating attenuators or platforms, maybe combined with WTGs, will be ideal for this site.

Financial issues and detailed analysis will be carried out in MERMAID work packages 4 and 7.

# 4 Business Case Summary

The MUP study cases present promising examples of future innovative MUPs. The technical solutions to installing an MUP have been proposed in this report and will be summarised here.

## 4.1 Installation of 1000MW Offshore Wind Farm at North Sea Site

A new type of floating installation vessel has been selected as an example to conduct the installation of future large 10MW WTG foundations. Installation is performed in two operations: pre-piling and jacket installation. Standard jack-up vessels are utilized to simulate the turbine installation operations. The main results from the case study are given as follows:

- The preferred solution for the jacket installation is to use pre-installed piles. The piles are installed with the use of a purpose built template to guide the piles as they are hammered into the seabed. Piling and jacket installation will be undertaken from a FIV-DP vessel, which loads piles for 4 WTG locations or alternatively three jackets per voyage. Grouting between each set of piles and jacket will be carried out from a smaller standalone vessel.
- A jack-up vessel is recommended for installation of the WTGs. The vessel can carry three 10MW WTGs per voyage which can be installed with five lifts. The first lift is the tower then the nacelle with the hub attached and final lift is the three blade rotor.
- The substation design proposed is a self-installing platform, also called a mobile jack-up. This technology is developed in such a way that the substation is floated out from the yard and supported by anchor handling tugs; it is towed to the substation on site.
- The cable installation is divided into two separate sections, infield and export cables. Infield cables are trenched between the base of the WTGs and the substation. Such trenching can be carried out from a smaller cable laying vessel. The two export cables that will be laid between the offshore substation and the onshore substation and will be installed with the use of a larger cable layer vessel.
- An installation time schedule was presented for each of installation operation. It is estimated that it will take one year to install all the components for the 1000MW OWF in the North Sea.
- O&M requirements for the OWF include both scheduled and unscheduled maintenance. Scheduled maintenance involves daily surveillance and intervention, as well as a yearly service campaign. Typical reasons for unscheduled maintenance are gear box problems, lighting, extreme wave loads, transformer issues, sea cable failures etc. Onshore and offshore O&M bases are considered. Several types of offshore O&M base options are taken into account. It is estimated that seven persons will need to be transported every day to the offshore site for the daily surveillance and intervention maintenance. Crew vessels for transport between the O&M base and the OWT are proposed. More permanent solutions for larger service vessels are also considered during the yearly service campaign.

The key issue for all installation activities is the need to have a suitable vessels to conduct the installation work. The solutions in this report have been developed based on available and planned vessels in the market place, in order to enable the development of the 1000MW OWF.

Port/base operations and any pre-transport of piles, jackets, WTGs, cables and substation have not been considered in this document.

The brief description of the installation of the monopile foundation is presented in Appendix D, along with transport considerations.

## 4.2 Installation of 1000MW Offshore Wind Farm at an Atlantic Site

The summary of the installation of 100 units of 10MW floating offshore WTGs at an Atlantic site is as follows:

- An integrated installation methodology, meaning the complete WTG structure (foundation, tower, nacelle, rotor), or large parts of the complete structure, are installed as one piece, and it is the preferred solution for the installation of floating offshore WTGs; in many cases also for bottom-fixed offshore WTGs.
- For a three-bladed Hywind type WTG, a vertical assembly and a tow-out methodology is presented.
- For a two-bladed Hywind type WTG, a vertical assembly method offshore at a sufficient depth (~260m) is the preferred solution. For a two-bladed turbine no high lifting operations are required and weather limitations for the operations therefore become less severe.
- The need for O&M is difficult to assess. However, the present requirement at an OWF with a similar number of WTGs at a similar distance from shore is three service vessels and 30 people on average every day.

The installation procedure of the floating WTG Hywind is presented in Appendix E.

## 4.3 The Synergies and Risks of MUP

The main four aspects of MUP are summarized as follows.

**Increase yields:**

- Annual electricity from wind power: 471 MEUR (3300GW/h with annual average wind speed 9.5m/s)
- North Sea site study case: Aquaculture salmon production yield reaches 50-60% of electricity yield
- Atlantic site study site: Aquaculture European sea bass yield amounts to 76-89% of electricity yield
- High quality sea foods

**Synergies:**

- Sharing of infrastructures, installations and services
- Potential joint technology developments

**Impact on the environment:**

- Ocean space sharing: turn conflicts into cooperation
- Offshore aquaculture: reduce pollution in (populated) coastal areas
- Details of environmental impacts are described in MERMAID’s work package 4.

**Disadvantages:**

- Offshore Wind Farm:
    - Impacts of extra marine biofouling on wind structures due to aquaculture nutrients
    - Risks of installation conflicts and daily aquaculture O&M activities within the OWF
- Aquaculture farm: Effects from WTGs, e.g. noise, electrical cable magnetic field changes etc.
- Licensing issues may arise

An offshore wind farm involves high investment. Thus, it is important to study and deploy risk management methodologies. The aquaculture farming facilities within the offshore wind farm must be taken beyond the experimental level. The technology development of aquaculture farming under offshore harsh conditions would be a subsequently challenging task.

The quantitatively evaluation of the synergies and disadvantages of the proposed MUP comparing to a 1000MW wind farm will be presented in the following deliverable D6.3 with regard to the following three criteria: yield, cost, and impacts on the marine environment during the construction, operation and maintenance phases.

## Appendix A: Assumptions of the MUP Case Study at the North Sea Site

The North Sea site conditions used in this Multi-Use Platform (MUP) study are based on the conditions of the offshore wind farm (OWF) Gemini in the North Sea, with some modifications. The modifications aim at including future wind farm challenges, such as Dogger Bank.

The site conditions and Wind Turbine Generators (WTGs) in this MUP study are different from Gemini. Firstly, the modified site conditions are as follows.

- Water depth: 40m
- 100km from service port
- 1000km from production port

Secondly, the OWF is assumed to have 100 units of future large WTG 10MW with jacket foundation. The dimension and weight of 10MW WTG and jacket foundation versus 5MW (based on REpower 5M installed at Alpha Ventus) are listed in Tables A.1 and A.2. The dimension and weight estimation of 10MW aims at the marine operation evaluation.

**Table A.1** Dimension and weight of 10MW WTG versus 5MW WTG

| Turbine size | 5MW | 10MW (estimation) |
|---|---|---|
| **Rotor diameter** | 126m | 200m |
| **Weight of nacelle with rotor and hub** | 410 ton | 700 ton |
| **Tower height** | 92m | 110m |
| **Tower mass** | 300 ton | 500 ton |

**Table A.2** Dimension and weight of 10MW jacket foundation versus 5MW WTG

| | Wind turbine size | 5MW | 10MW (estimation) |
|---|---|---|---|
| **Jacket** | ***Dimensions*** | L*W*W: 56 * 20m * 20m | L*W*W: 66 * 27m * 27m |
| | ***Weight*** | 510 ton | 1000 ton |
| **Pile** | ***Dimensions*** | L*D: 50 m* 1.1m | L*D: 50m * 2.5m |
| | ***Weight*** | 315 ton | 700 ton |

## Appendix B: Description of the Offshore Wind Farm Gemini in the North Sea.

Description of the offshore wind farm Gemini in the North Sea is found in detail in MERMAID deliverable 7.1 [16]. A brief summary is given in this section. The project Gemini consists of 2 * 300MW OWFs in the Netherlands (NL) shown in Figure B.1.

- Project Gemini is located at one of the best offshore wind locations in NL with average wind speeds of 10m/s (confirmed by Garrad Hassan) → Estimated annual production for 600MW: 2 300GW/h
- Buitengaats (300MW) and ZeeEnergie (300MW) both have an approved permit and a feed-in tariff ('SDE") granted by the Dutch government
- The awarded SDE totals a maximum subsidy of €4.4 billion → guaranteed income over 15yrs
- Project Gemini's revenues consist of a (1) the Wholesale electricity sales under the PPA (Power Purchase Agreement), plus (2) the Subsidy income; together combined result in an annual fixed revenue stream
- Electricity for 650 000+ Dutch households per annum which equals to a reduction in emissions of 1.25 million tonnes of $CO_2$
- Project Gemini will most likely be the only large Dutch OWF project for the foreseeable future
- A geophysical study by Fugro confirmed excellent soil conditions for installation
- The onshore grid connection is owned by Tennet in Eemshaven

The investigation results, with regard to the current policy, management and planning strategy, were based on the review of (scientific) publications and government documents by MERMAID work package 2 and are given as follows.

- The Dutch marine spatial policy stresses two main principles: (1) the need for space-efficient use, such as multiple use of offshore platforms (e.g. offshore wind farms), and (2) the need to follow an ecosystem approach.
- The wind energy sector committed itself to a substantial cost reduction of 40% of the total costs per MW/h. To achieve this, every discipline involved in offshore energy production is kept under constant review.
- The Dutch mussel culture sector sees market opportunities for a total yearly production of 100 000tons of mussels; this is almost twice as much as the current production and can only be achieved if new areas for mussel production become available.
- There are opportunities to achieve the different objectives of all stakeholders (the government, the wind sector, and the mussel culture sector) by combining offshore wind energy production with offshore aquaculture.

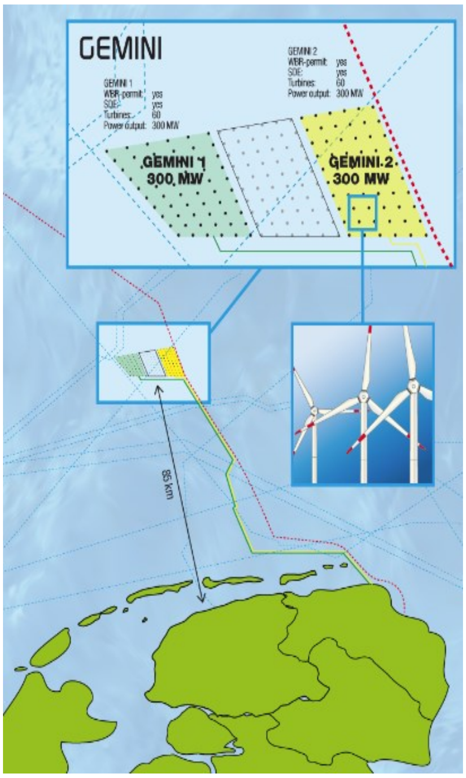


**Figure B.1** Location of Dutch OWF Gemini

## Appendix C: The Wind and Wave Energy at Four MERMAID Pilot Sites

### C.1 Summary of Wind Speed and Wave Energy at Four Sites

The summary of wind speed and wave energy potential at four sites, based on hourly time series and on the SKIRON model, is given in the following figures. The hourly time series are provided by the site managers of WP7 of the MERMAID project.

### C.2 Wind Data at Four Sites

The wind data is given in Weibull distribution based on SKIRON model and in an hourly data series.

The Weibull distribution is based on SKIRON model. SKIRON is a numerical modelling tool developed by the University of Athens. With SKIRON it is possible to analyse a 5km * 5km horizontal area. Based on the numerical analyse they can describe the atmospheric conditions. The model provides meteorological parameters like wind speed, wind direction, air temperature and mean sea level pressure where wind farms operate. Based on this analysis they estimate the average wind speed and the two Weibull parameters (A and k) for the relevant locations. The data is valid 100 meters above sea level [18].

These two Weibull parameters are then plotted into the cumulative Weibull distribution function to illustrate the wind distribution through a year.

$$f(x) = 1 - e^{-\left(\frac{V}{A}\right)^k}$$

Where, V is wind speed, and A and k are the mentioned Weibull parameters.

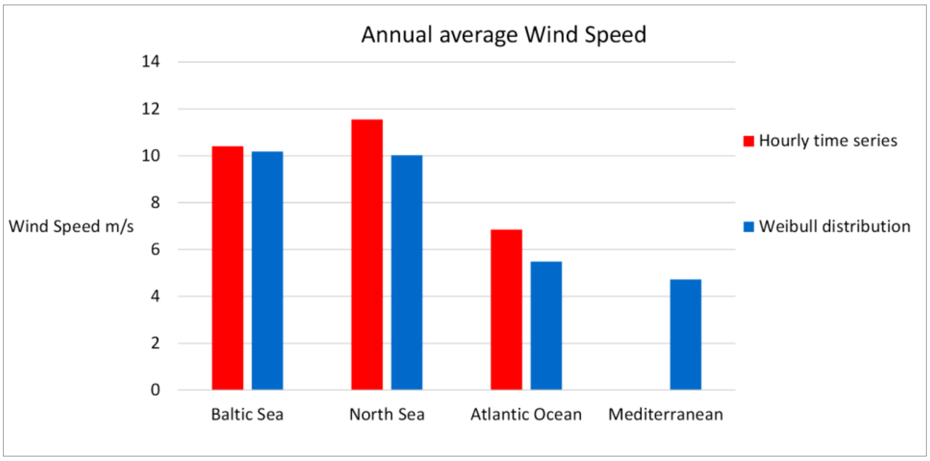


**Figure C.1** Average annual wind speed at four sites [**17**]

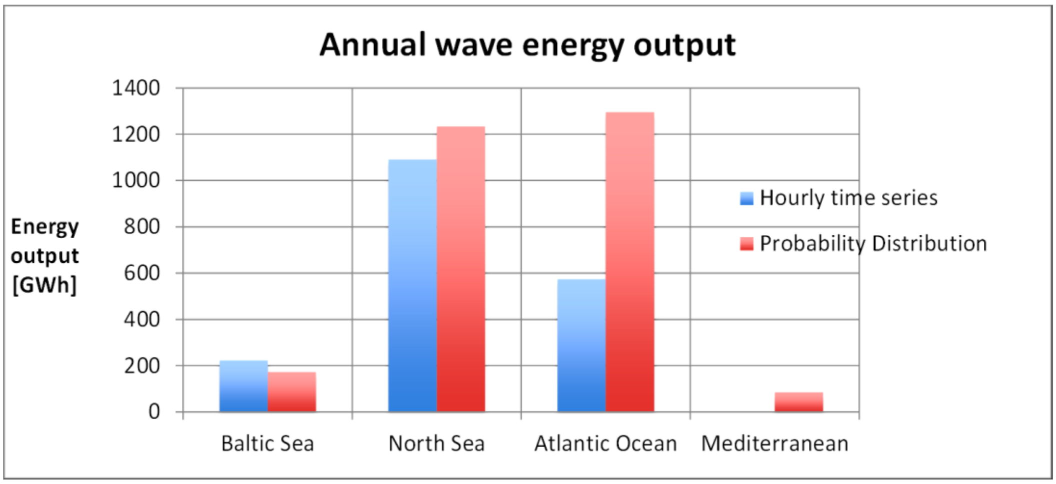


**Figure C.2** The potential annual wave energy output at four sites, using the Pelamis WEC [**17**]

### C.2.1 Wind data at the North Sea site

Parameters A and k of the Weibull distribution based on the SKIRON model at the North Sea are given as follows: A = 10.7; k = 2.24 [18]. The wind speed distribution based on the SKIRON model is shown in Figure C.3A, the wind speed distribution based on an hourly time series is shown in Figure C.3B and the hourly wind speed time series over one year at the Gemini OWF is shown on Figure C.3C.

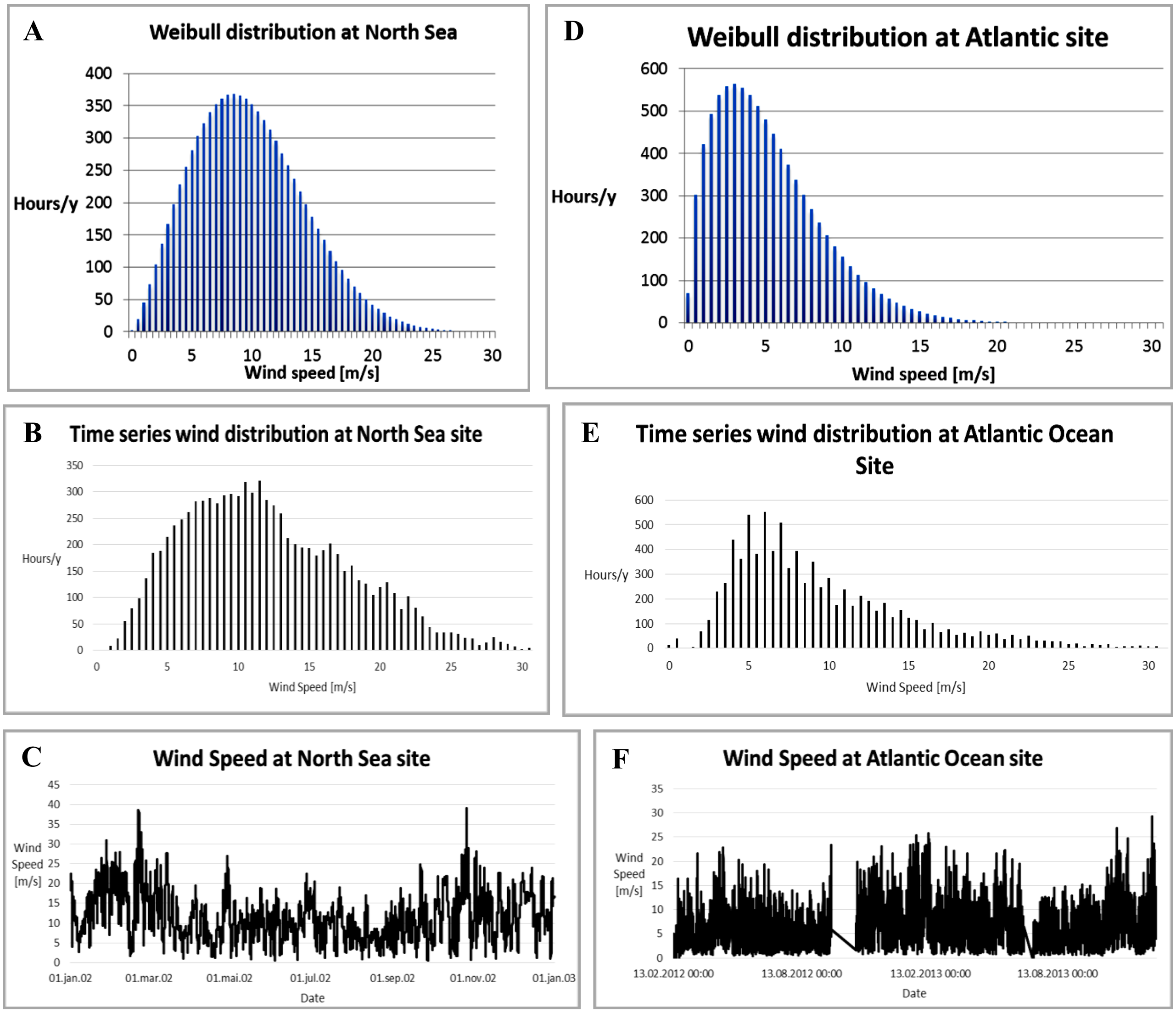


**Figure C.3** Wind Speed at the ***North Sea Site:*** **A.** SKIRON model hourly wind distribution; **B.** Hourly wind distribution at Gemini OWF; **C**. Wind speed at Gemini over a period of one year; and at the ***Atlantic site***: **D.** SKIRON model hourly wind distribution; **E.** Hourly wind distribution; and **F.** Wind Speed at COS over a period of one and a half year.

### C.2.2 Wind data at the Atlantic site

Parameters A and k of the Weibull distribution based on the SKIRON model at the Atlantic are:

A = 5.64; k = 1.53 [18]. The wind distribution based on the SKIRON model is shown in Figure C.3D, the wind speed distribution based on an hourly time series is illustrated in Figure C.3E and the hourly wind speed time series over a year and half is shown on Figure C.3F.

### C.2.3 Wind data at the Baltic Sea site

The parameters A and k of the Weibull distribution based on the SKIRON model at the Baltic Sea site are:

A = 10.87, k = 2.2 [18]. The wind distribution based on the SKIRON model is shown in Figure C.4A, the wind speed distribution based on an hourly time series is illustrated in Figure C.4B and the hourly wind speed time series over 3 years is shown in Figure C.4C.

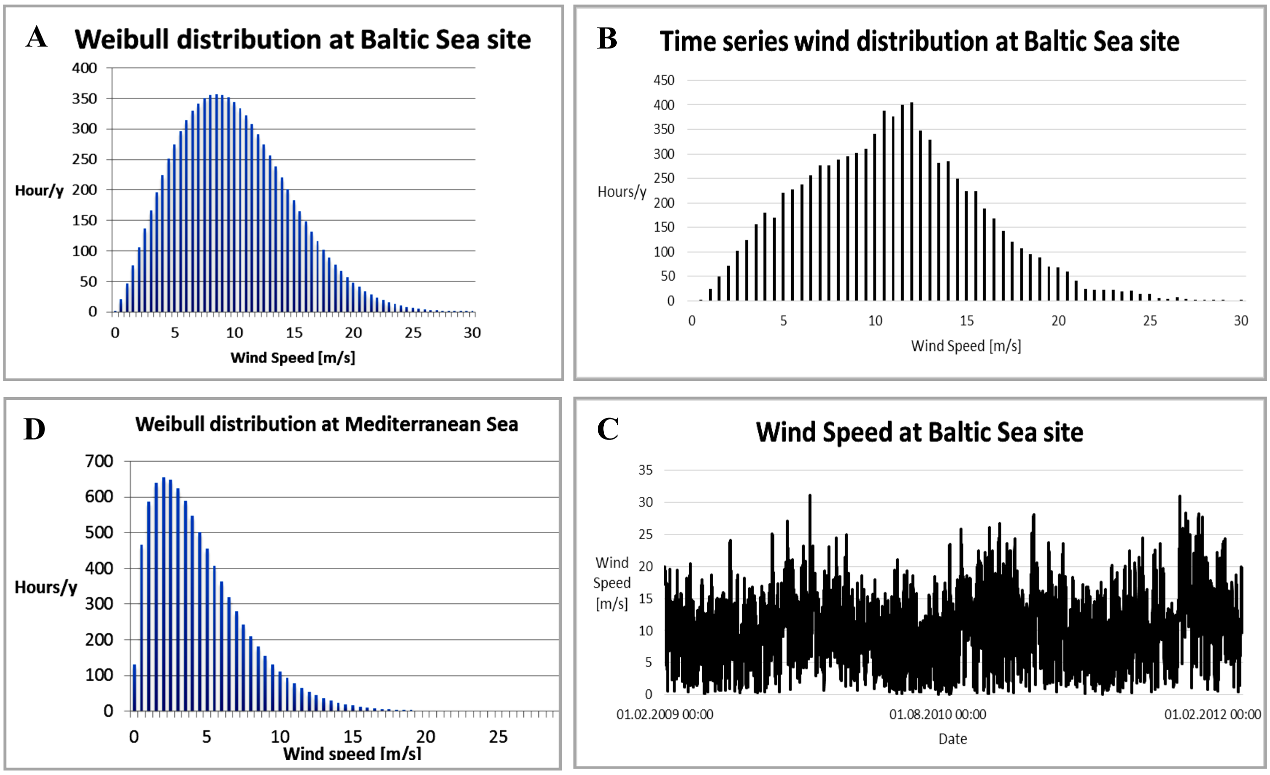


**Figure C.4** Wind Speed at the ***Baltic Sea Site:*** **A**.SKIRON model hourly annual wind distribution; **B.** Hourly wind distribution at Kriegers Flak; **C**. Wind speed at Kriegers Flak over a period of three years; and **D**. SKIRON model annual hourly wind distribution at the ***Mediterranean Sea site***.

### C.2.4 Wind data at the Mediterranean Sea site

The parameters A and k of the Weibull distribution based on the SKIRON model at the Mediterranean Sea site are: A = 4.76, k = 1.41 [C2] (Fig. C.4D).

## C.3 Wave Energy Matrix

The wave energy estimation is based on the Pelamis power matrix. Table C.1 provides the produced electricity as a function of the significant wave height, $H_{s,}$ and the power period, $T_p$.

**Table C.1.** Pelamis Power matrix [17]

| ***Te*(s)*Hs*(m)** | **5** | **5.5** | **6** | **6.5** | **7** | **7.5** | **8** | **8.5** | **9** | **9.5** | **10** | **10.5** | **11** | **11.5** | **12** | **12.5** | **13** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0.5** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **1** | 0 | 22 | 29 | 34 | 37 | 38 | 38 | 37 | 35 | 32 | 29 | 26 | 23 | 21 | 0 | 0 | 0 |
| **1.5** | 32 | 50 | 65 | 76 | 83 | 86 | 86 | 83 | 78 | 72 | 65 | 59 | 53 | 47 | 42 | 37 | 33 |
| **2** | 57 | 88 | 115 | 136 | 148 | 153 | 152 | 147 | 138 | 127 | 116 | 104 | 93 | 83 | 74 | 66 | 59 |
| **2.5** | 89 | 138 | 180 | 212 | 231 | 238 | 238 | 230 | 216 | 199 | 181 | 163 | 146 | 130 | 116 | 103 | 92 |
| **3** | 129 | 198 | 260 | 305 | 332 | 340 | 332 | 315 | 292 | 266 | 240 | 219 | 210 | 188 | 167 | 149 | 132 |
| **3.5** | 0 | 270 | 354 | 415 | 438 | 440 | 424 | 404 | 377 | 362 | 326 | 292 | 260 | 230 | 215 | 202 | 180 |
| **4** | 0 | 0 | 462 | 502 | 540 | 546 | 530 | 499 | 475 | 429 | 384 | 366 | 339 | 301 | 267 | 237 | 213 |
| **4.5** | 0 | 0 | 544 | 635 | 642 | 648 | 628 | 590 | 562 | 528 | 473 | 432 | 382 | 356 | 338 | 300 | 266 |
| **5** | 0 | 0 | 0 | 739 | 726 | 731 | 707 | 687 | 670 | 607 | 557 | 521 | 472 | 417 | 369 | 348 | 328 |
| **5.5** | 0 | 0 | 0 | 750 | 750 | 750 | 750 | 750 | 737 | 667 | 658 | 586 | 530 | 496 | 446 | 395 | 355 |
| **6** | 0 | 0 | 0 | 0 | 750 | 750 | 750 | 750 | 750 | 750 | 711 | 633 | 619 | 558 | 512 | 470 | 415 |
| **6.5** | 0 | 0 | 0 | 0 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 743 | 658 | 621 | 579 | 512 | 481 |
| **7** | 0 | 0 | 0 | 0 | 0 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 676 | 613 | 584 | 525 |
| **7.5** | 0 | 0 | 0 | 0 | 0 | 0 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 686 | 622 | 593 |
| **8** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 690 | 625 |

# Appendix D: Transport and Installation Methods for Monopiles

Monopiles are the most commonly used foundation, with up to 30m water depth, due to the structural simplicity, manufacturing and installation cost. It is estimated that more than 75% of all installations to date are founded on monopiles [19]. A typical monopile is a long tube with a diameter of 4 to 5 meters. The monopile typically weighs around 500tons, making it one of the lighter support structures available. On deeper sites, like Walney2, monopiles can weigh up to 810tons and are up to 69m long, in a water depth of 30m.

The piles to be pre-installed at the 100 WTG locations at the North Sea site have the following assumed dimensions:

| | |
|---|---|
| Diameter | 2.438m |
| Length | ⩽ 54m |
| Weight | ⩽ 190tons |
| Wall thickness | 50mm |
| Pile stick-up | 2 - 4m |

Monopiles are normally driven into the sea bed by hydraulic drills and/or hammers. A drive-drill-drive method, where both hammer and drill equipment are utilised in parallel, will be considered if the piles meet refusal. The installation vessel has sufficient deck storage capacity to handle both sets of equipment in parallel. A transition piece with a slightly different diameter is placed on top of the monopile. The transition piece is pre-assembled onshore with a connecting flange for the tower, an access platform, ladders, tubes for cables and other secondary structural members. The piece is connected with the monopile through an overlap with length of around 1.5 times the monopile diameter [20]. The annulus between the pile and the transition piece is grouted with high-density concrete and the transition piece is adjusted to true verticality.

## D.1 Transport

In general, there are two ways to transport monopiles: towed on-board a barge or an installation vessel or capped and wet towed [21]. The choice depends on the size and weight of the monopile, and the capacity of the vessel used. The transition pieces are also either towed on a barge or on the installation vessel.

If transported on a barge, the length of the barge should be long enough to carry the monopiles. It seems improbable that the pile will be cut in pieces for transport and be welded together before installation. This means that the transport area needed on a barge will be at least 50m long. If the monopiles are transported on installation vessels, the vessel should have enough crane capacity and deck load to lift a monopile clear of the water. Vessels with lower capacity cranes will need a feeder vessel to transport the monopiles since floating lifts are not normally used, or will need to use a wet tow.

Due to an increasing monopile weight for larger capacity WTGs, it is very expensive to use large installation vessels to carry out the operations. A wet tow method can be used if the distance to shore is small and the site is characterised by calm weather (e.g. Anholt). If the piles are towed to location, their design must include watertight compartments or attachment points to external compartments. Probably two towing tugs will be needed for self-floated transport. The wet tow of a single floating monopile has already been used in the North Hoyle and Walney2 OWF [22, 23, 24]. The transport of more than one pile at a time using this method is not unthinkable, with a proper connection of the monopiles during towing.

## D. 2 Installation

The installation of a monopile in general includes two main steps: upending (Fig. D.1A) and driving/drill operations (Fig. D.1B). After vessel arrival on site, the pile is upended and lowered through the water so that it sits vertically on the sea bed. A hydraulic hammer is placed on top of the pile and it is driven into the seabed to a predetermined depth. A rocky subsurface may prevent driving operations, in which case a drill will be inserted into the pile to drill through the substrate.

After the monopile is secured in the seabed, a transition piece is lifted and grouted onto the pile. In some cases the transition piece may be bolted. The transition piece is typically installed immediately after piling, by the same vessel that drove the pile; if two vessels are employed during the installation, a separate vessel may follow behind and install the transition piece.

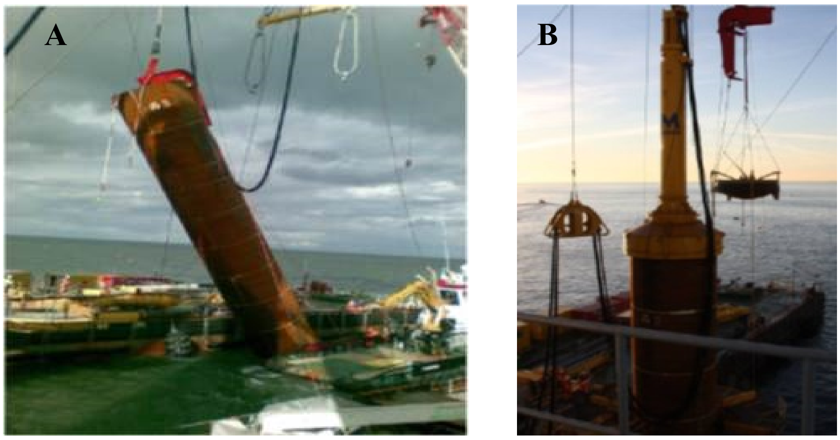


**Figure D.1** Upending a monopile (**A**) and piling a monopile (**B**)

## D. 3 Challenges

The challenges faced by monopile installation are the lifts and jack up operations in the open water, because they are weather sensitive. Additionally the operation of upending the long monopiles in the water is also weather sensitive, compared to upending on-board, due to the hydrodynamic loads on the pile. If upending is carried out on board of an installation vessel, the monopile handling and upending tool could be used to make operations safer and increase the possible operational sea conditions. For examples of monopile handling and upending tools see [25]. Therefore, a comprehensive analysis should be carried out before choosing a solution.

## Appendix E: Installation of a Floating Wind Turbine Generator (Hywind)

Statoil's installation experience of Hywind 2.3 is presented in this appendix.

### E.1 General Information

Hywind (Fig. E.1) is the world's first floating MW-scale WTG, and it has been successfully operated since September 22nd, 2009. The key technical data is given as follows:

- Turbine size: 2.3MW
- Turbine weight: 138tons
- Turbine height: 65m
- Rotor diameter: 82.4m
- Displacement: 5300$m^3$
- Diameter at water line: 6m
- Water depths: 120-700m
- Mooring: 3 lines

**Figure E.1** Floating WTG Hywind

The components of Hywind Demo were fabricated at different locations and then transported to an onshore assembly site in Åmøyfjorden close to Stavanger (Fig. E.2A). The sequence of the installation operations onshore, towing to offshore and offshore were as follows:

- Assembly of the main structural components was done in sheltered waters in Åmøyfjorden. The nearby Dusavika quay facility (Fig. E.2B) was also used during the onshore assembly phase.
- After the tower sections and the rotor had been mounted on top of the transition piece, Hywind Demo was towed to the offshore site.
- The lower part of the mooring system and the power cable were pre-installed at the offshore site, and were hooked up with Hywind Demo when it arrived on site.

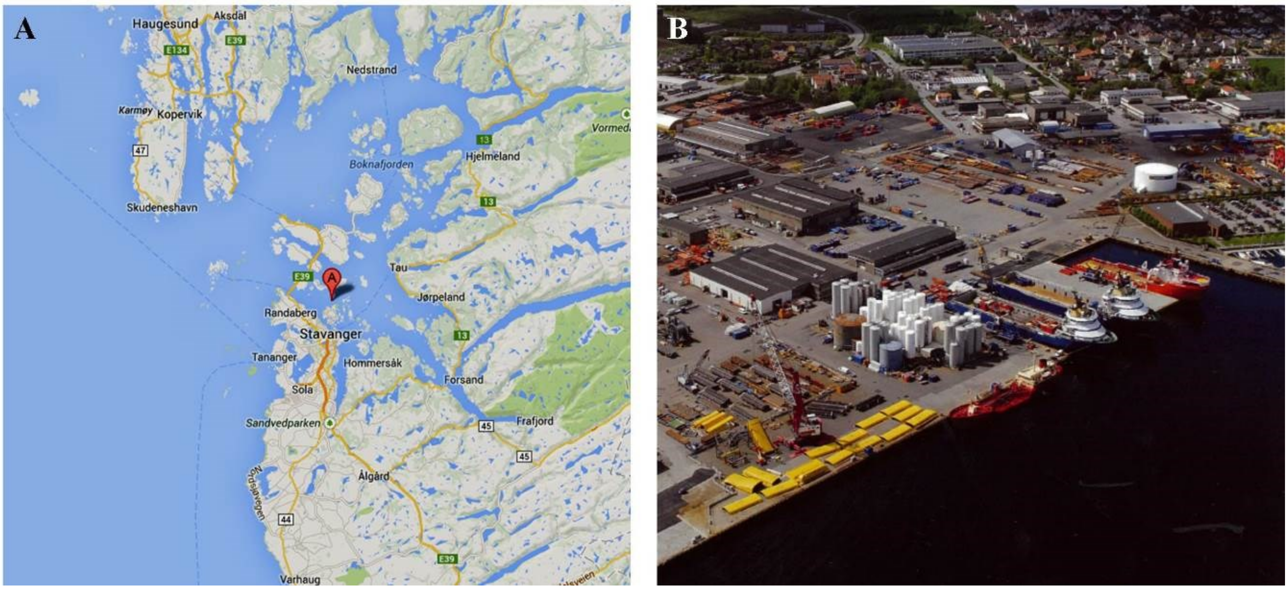


**Figure E.2** Åmøyfjorden near Stavanger (Google Maps) **(A)** and Norsea A.S. Dusavik quay facility **(B)**

## E.2 Production and Transport

The sub-structure and the transition piece were produced at Technip's construction yard in Pori, Finland. They were mounted together and towed 1760km (Fig. E.3A) in one piece (Fig. E.3B) to the assembly site in Åmøyfjorden. The WTG tower sections, the rotor blades and the hub were produced by Siemens and transported to the quay at Dusavika using a transport barge. The rotor was then assembled and the components were prepared for the assembly operations.

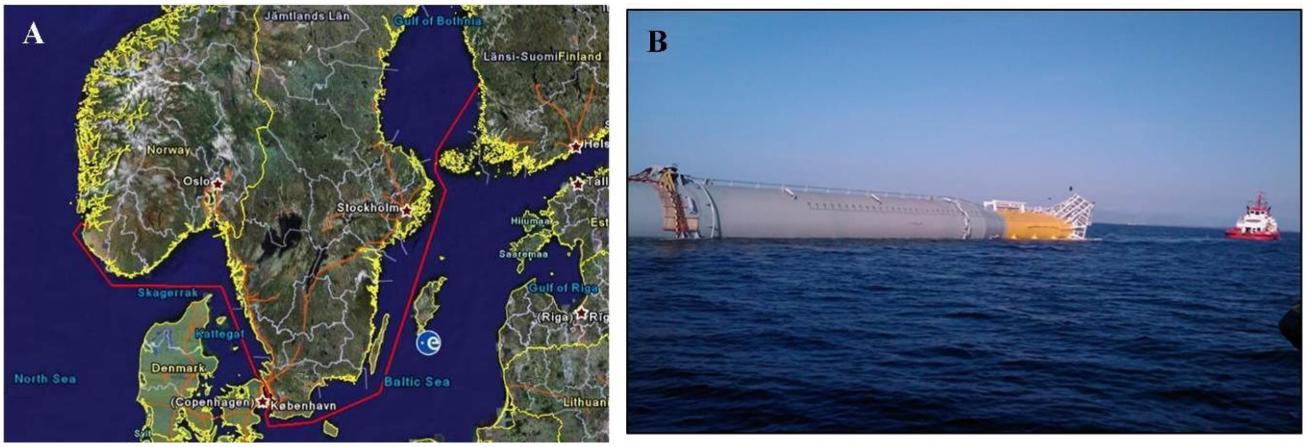


**Figure E.3** Tow route Pori, Finland to Stavanger, Norway **(A)** and Hywind Demo sub-structure and transition piece **(B)**

## E.3 Assembly

### E.3.1 General

The operations to assemble the main components of Hywind Demo (sub-structure, tower sections and rotor) were carried out in the sheltered waters of Åmøyfjorden. The main operations were:

- Up-ending and ballasting of the sub-structure and transition piece
- Inshore assembly of rotor
- Inshore assembly of upper tower and nacelle
- Installation of lower tower section
- Installation of upper tower section (including nacelle)
- Installation of rotor

The lifting barge Conlift (Fig. E.4) was used during the inshore assembly operations.

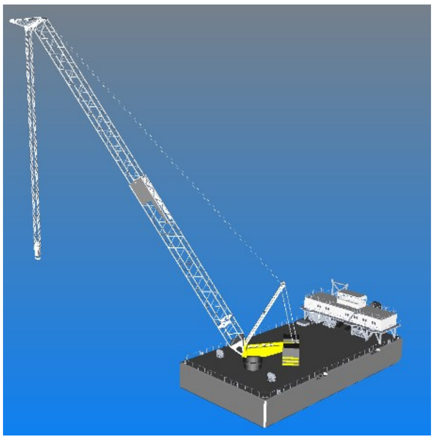


**Figure E.4** Inshore *Conlift* lifting barge

### E.3.2 Up-ending and ballasting

Up-ending of the sub-structure was done by slowly filling the horizontally floating sub-structure with water (Fig. E.5). On the left of Figure E.5, a barge can be seen; the barge was moored at the assembly site and used as a platform for equipment and personnel during the rest of the assembly operations.

After Hywind Demo had become vertical it was attached to the stern of the barge. The structure was then ballasted further with water and olivine gravel, until the desired draft for the next phase of the operation at Åmøyfjorden was reached.

**Figure E.5** Hywind Demo up-ending of the sub-structure in Åmøyfjorden

### E.3.3 Onshore assembly

The hub and the rotor blades arrived at Dusavika as four separate components and were put together on the quay. The upper tower segment and the nacelle also arrived as separate components to be assembled in Dusavika. A picture showing the assembled rotor and the upper tower segment, with the nacelle on top, can be seen in Figure E.6.

**Figure E.6** Rotor with hub, upper tower segment and nacelle on the quay at Dusavika

### E.3.4 Installation of lower tower section

The lower tower segment was picked up on the quay-side by the Conlift lifting barge and transported out to the sub-structure while suspended on Conlift’s crane. Conlift was then moored to the barge at the sub-structure and the lower tower section was lowered onto the top of the transition piece (Fig. E.7) and secured in place.

**Figure E.7** Assembly of lower tower section

### E.3.5 Installation of upper tower section and nacelle

After installing the lower tower section, Conlift returned to the quay-side to pick up the upper tower with the nacelle on top. This component was then installed on top of the lower tower section, using the same procedure as the one that was used for putting the lower tower onto the transition piece. A picture from the operation taken just before the upper tower is put down onto the top of the lower tower can be seen in (Fig. E.8).

**Figure E.8** Assembly of the upper tower section with the nacelle at Åmøyfjorden

### E.3.6 Installation of the rotor

The procedure for installing the rotor and hub onto the nacelle was similar to the procedures described in the two preceding sections, at Åmøyfjorden. Conlift picked up the rotor at the quay-side, transported it out to the assembly site and lifted it onto the nacelle (Fig. E.9). A tailor-made hook was designed for this operation. This hook was attached to the flange at the nacelle, so that the rotor could be hanged off there before the final attachment to the bolts at the flange was done. This allowed for a controlled connection.

The floating crane vessel Conlift and the installation platform barge can be seen in Figure E.9.

**Figure E.9** Rotor lifted onto the nacelle using Conlift

### E.3.7 Tow-out

After the main components had been assembled inshore at Åmøyfjorden, Hywind Demo was towed to the offshore site.

The tow-out was carried out using three tugs. The biggest one (the Normand Pioneer is to the far left in the picture in Fig E.10) was used for pulling and the other two smaller tugs were used to assist (stabilise) the tow (Fig. E.10).

**Figure E.10** Vessels used in the tow-out from the inshore assembly site.

## Appendix F: Service Vessels for the Future Wind Farm – A Literature Review

Current wind farm service vessels (WFSVs) are generally less than 24m long, therefore generally coded by the Maritime and Coastguard Agency (MCA) as Cat 2, restricting operation to 60nmi from a safe haven. The regulations for ships greater than 24m are more onerous and stipulate additional safety features, however, they can operate at a greater distance from a safe haven, which is more suited for future OWFs. The construction of wind farms further than 60nmi will produce a radical change in the types of vessels and methods used for access. Up to date, regulations will provide poor opportunities to class the WFSVs operating in this region. The regulations currently in place are not adequate for the work being carried out; better developed regulations and more standardised access requirements will make it safer to access OWFs. Currently there is no harmonised international code or regulation specifically for WFSVs; operators are classifying vessels with either MCA or DNV (Det Norske Veritas). To work further offshore would require an MCA Cat 1 vessel (up to 150nmi) or a vessel coded by a classification society such as DNV or GL (Germanischer Lloyd). Most recent OWFs can be serviced by MCA Cat 2 vessels and since fully classed vessels are more expensive to charter, because the build costs are higher, MCA Cat 2 vessels are more frequently used. The International Maritime Contractors Association and the National Workboat Association are two additionally important stakeholders involved in regulating the WFSV industry.

**Figure F.1** MPI Don Quixote during a Bow Transfer Operation

The health and safety of the offshore WTG technicians who commute to the wind farm on a WFSV is becoming more and more important, as wind farm operators aggressively pursue increases in the limits for O&M access. As wind farms are constructed further offshore, WFSVs will have to travel greater distances in more challenging conditions. Larger boats are more capable with larger Significant Wave Heights (Hs) and wind speed, but the motion stress placed on personnel must be taken into account. A challenge facing the industry is the time technicians can spend in transit each day. A 12 hour day for technicians is standard when the commute is factored in the shift duration; fatigue levels due to the 12 hour shift are very high. The technicians that service OWFs are not seafarers and hence suffer more severely from motion induced fatigue than other offshore workers. WFSV designers have mitigated these concerns by integrating features such as windows that enable passengers to see the horizon and vibration and suspension seating. Extremely high safety and quality standards will define the future of the offshore wind industry.

## F.1 Current wind farm service vessels

The vast majority of WFSVs are catamarans but monohulls, Small Water Plane Area Twin Hulls (SWATHs), semi-SWATHs, trimarans, amplemans and floatels are also utilised. A brief description of each vessel category is presented.

### F.1.1 Catamaran

High speed catamarans (Fig. F.2), with a cruising speed of 15-25knots and generally between 15-24 metres in length, are mainly utilised by the OWF industry. WFSVs can usually carry a cargo in the range of 3-15ton. Typically they are made of aluminium, though glass reinforced plastic and other composites have been used. The aim is to get to the wind farm a quickly as possible whilst keeping seasickness and fatigue at a minimum. Most of these vessels use the industry standard method of bow transfers, using a reinforced bow with a rubber fender; a relatively large bollard pull allows the connection to be maintained safely for most wave spectrums with a Hs of 1.5m.

**Figure F.2** Typical WFSV Catamaran

### F.1.2 Monohull

Monohulls can provide a similar service to that of catamarans but its seakeeping abilities are different from the conventional WFSVs, making them more suitable for certain applications. Monohulls are also limited at a Hs of 1.5m.

### F.1.3 Small Water Plane Area Twin Hulls

SWATHs (Small Water Plane Area Twin Hulls) offer significantly more stability during transit and transfer, resulting in a limit Hs of 2-2.5m. The increase in stability is due to the small water plane area and deeper draft, however, these features make SWATHs cost more to run. They are also expensive to build due to design structural requirements. Therefore, SWATHs (Fig. F.3) are not as widely used as one would first imagine, though this may change with the advent of further OWFs.

**Figure F.3** Natalia Bekker, SWATH Vessel

### F.1.4 Semi-SWATHs

There are also semi-SWATHs available that provide a compromise between a SWATH and a Catamaran.

### F.1.5 Trimarans

Trimarans have an advantage of being faster, more efficient and more stable than catamarans. Companies such as Mobimar use trimarans extensively in their fleet.

The tables below are a non-exhaustive list of WFSV's, to provide an insight to the vessels currently used in the industry.

**Table F.2** Current Catamaran examples of WFSVs

| **Company** | **Name** | **Length** (m) | **Service Speed** (knots) | **Passengers** |
|---|---|---|---|---|
| **A2 Sea** | Wind Supporter | 24 | 18.6 | 12 |
| **A2 Sea** | WIND TRANSFER | 21 | 20 | 12 |
| **Windcat Workboats** | WindCat MK 1 Series | 15 | 25 (max) | 12 |
| **Windcat Workboats** | WindCat MK 2 Series | 18 | 25 | 12 |
| **Windcat Workboats** | WindCat MK 3 Series | 18 | 26 | 12 |
| **Windcat Workboats** | WindCat MK 4 Series | 27 | 26 | 45 |
| **Windcat Workboats** | Windspeed Series | - | 24 | 12 |
| **MPI Workboats** | MPI Dorothea – MPI Dulcinea | 17.5 | 22 | 12 |
| **MPI Workboats** | MPI Don Quixote | 20.6 | 23 | 12 |
| **MPI Workboats** | MPI Altisidora – MPI Lucinda – MPI Sampson – MPI Trifaldi | 19.15 | 22 | 12 |
| **MPI Workboats** | MPI Cardenio – MPI Cervantes | 17.5 | 22 | 12 |
| **MPI Workboats** | MPI Rosinante | 16 | 25 | 12 |
| **MPI Workboats** | MPI Rucio | 16 | 25 | 12 |
| **MPI Workboats** | MPI Sancho Panza | 15.48 | 25 | 12 |
| **MPI Workboats** | MPI Napoleon – MPI Snowball | 22 | 23 | 12 |
| **South Boats** | 16 WFSV | 16 | 20 | 12 |
| **South Boats** | 17 WFSV | 17.47 | 22 | 12 |
| **South Boats** | 18 WFSV | 19.08 | 22 | 12 |
| **South Boats** | 19 WFSV | 19.5 | 21 | 12 |
| **South Boats** | 21 WFSV | 21.01 | 25 | 12 |
| **South Boats** | 22 WFSV | 22.8 | 23 | 12 |
| **South Boats** | 24 WFSV | 25.14 | 23 | 12 |
| **South Boats** | 26 WFSV | 26.77 | 23 | 12 |
| **BMT** | 24 WFSV | 24 | 26 | 12 |
| **BMT** | 20 WFSV | 20.4 | 24 | 12 |
| **BMT** | 17 WFSV | 17.4 | 25 | 12 |
| **Island Shipping** | Island Panther | 17 | 20 | 12 |
| **Island Shipping** | Island Tiger | 17 | 20 | 12 |
| **Sure Wind** | Sure Star | 26 | 22 | 12 |
| **Alicat** | Dalby Wharfe | 21 | 24 | 12 |

**Table F.3** Current Monohull examples of WFSVs

| **Company** | **Name** | **Length** (m) | **Service Speed** (knots) | **Passengers** |
|---|---|---|---|---|
| **A2 Sea** | Wind Supporter | 24 | 18.6 | 12 |
| **A2 Sea** | Wind Transporter | 25.1 | 24 | 12 |
| **A2 Sea** | ANHOLT WIND | 25.1m | 24 | 12 |
| **A2 Sea** | DJURS WIND | 25.1m | 24 | 12 |
| **A2 Sea** | WIND SUPPLIER | 32.2 | 25 | 24 |

**Table F.4** Current SWATH examples of WFSVs

| **Company** | **Name** | **Length** (m) | **Service Speed** (knots) | **Passengers** |
|---|---|---|---|---|
| **Wind MW** | Natalia Bekker | 26.4 | 18 | 12 |
| **A2 Sea** | SEA BREEZE | 24.76 | 18 | 24 |
| **A2 Sea** | SEA GALE | 24.76 | 18 | 24 |
| **A2 Sea** | SEA HURRICANE | 24.76 | 18 | 24 |
| **A2 Sea** | SEA STORM | 24.76 | 18 | 24 |
| **CTruk** | CWhisper | 20 | 20 | 12 |
| **Danish Yaughts** | SWATH 25M | 25 | 25 | 24 |

**Table F.5** Current Semi-SWATH and Trimaran examples of WFSVs

| **Company** | **Name** | **Length** (m) | **Service Speed** (knots) | **Passengers** |
|---|---|---|---|---|
| **BMT Nigel Gee** | XSS Cymyran Bay | 25.4 | 25 | 12 |
| **Austal** | Austal Wind Express TRI SWATH 27 - Cable Bay | 27.20 | 23 | 12 |
| **Mobimar** | Mobimar 23 Wind | 22.5 | 25 | 12 |
| **Mobimar** | Mobimar 18 Wind | 22.5 | 20 | 12 |

### F.1.6 Amplemans

The Ampleman (Fig. F.4) when used on a large enough craft (greater than 30m in length) can carry out transfers in sea states in excess of 3m Hs. An inventive device that can be installed on the deck of a larger vessel carries out motion reduction in six degrees of freedom.

**Figure F.4** Ampleman in Operation

### F.1.7 Floatel

Floatels are another type of vessel that is currently being used by the offshore wind industry to provide accommodation to staff at the OWF and to reduce transport to and from the OWF. Generally used for installation and construction crew, these vessels are the precursor to the mother ship. Floatels are converted cruise ships, ferries or ro/ro ferries.

## F.2 Future Vessels

A challenge for the WFSV industry is providing the right solutions for the future. Designs are constantly evolving and go through disruptive innovation, e.g. mini-jack-up vessels are continually evolving as the needs they need to meet change. The location of an OWF has a huge impact on WFSV requirements. WFSV designs are constantly evolving and continually changing with the requirements and expectations of OWF operators. WFSV designs are now evolving to meet the needs required for each vessel e.g. fast, comfortable, manoeuvrable at low speed, or stable at low speed, etc. These options must be considered in the design as they are not always compatible with each other. Examining the cost of a WFSV versus the day rate it will earn, affects design and what a WFSV operator can provide a client.

Trimarans and versions of SWATHs are being introduced into the industry, since catamarans may not be the preferred choice for UK Round 3 wind farms; the industry is evolving at a fast pace. Larger boats are naturally more robust and are regulated by stricter rules than smaller vessels. Larger vessels are more stable due to the length relative to wavelength ratio being smaller, which generally reduces the response amplitude operations.

Combining two opposing design restraints such as a good sea keeping ability and fuel efficiency is a challenge facing WFSV designers. One method to design future WFSVs is to identify the parameters that affect the desired performance. Significant wave height is the current metric from which designs are measured, but other factors place a large role in actually determining how a well a WFSV will perform its task. Factors such as wave direction and wave period, wind speed and direction, capacity, vessel speed, comfort, safety, fuel economy and charter costs are useful metrics. In addition, transit from port or mother ship to WTG, approach method to WTG, transfer from vessel to WTG, maintained speed, safety, capacity, fuel economy and operating cost, must all be taken into account; since modelling these metrics will allow operators to determine which systems are most appropriate for a specific location.

### F.2.1 Design and direction of the industry

Carbon Trust, with their offshore wind accelerator program, are promoting innovative designs in the industry, namely TranSPAR (Fig. F5), Fjellstrand WindServer, Nauti-Craft, Pivoting Deck Vessel, Autobrow system, Umoe Mandal Wave Craft. Each of these designs has the potential to revolutionise the industry. There are many other designs that are at the concept stage of development at research centres, including teams from universities and from large industry players to small start-ups.

**Figure F.5** ExtremeOcean TranSPAR Craft

### F.2.2 Small jack-up barges

DBB have designed a smaller than average jack-up barge, the Wind Server, to carry out O&M tasks. As a jack-up barge it can operate at a higher Hs of 2.6m

## F.3 Access Systems

### F.3.1 Transfer methods and developments

An issue for OWF maintenance operations is the acceleration and displacement waves induce on a WFSV, making it hazardous to transfer personnel to a stationary WTG, especially during high sea conditions.

The industry standard method of transferring personnel is to use the vessels high bollard pull to push the bow of the vessel into the WTG and with the help of a high friction rubber fender maintain contact with the WTG while the service personnel step across (Fig. F.6). Transfers using this method are generally restricted to 1.5m Hs or less. Accessibility is also affected by wave frequency, wind and current conditions.

**Figure F.6** MaXCCESS Transfer

To carry out transfers at high sea conditions, a motion compensating access system is a valuable tool in connecting the WFSV to the WTG and minimising the relative acceleration and displacement. This service can be provided by larger vessels with an access system or gangway, making transfers safer. A number of ‘walk to work’ systems have also been developed. These can entail a full six degrees of freedom motion stabilising device or a heave compensating bridging mechanism. They can then attach to the WTG so that personnel can safely walk onto the turbine as the bridge remains stationary, relative to the WTG. There are number of these systems on the market such as Amplemann, Damen shipyards Walk-to-work, Maxcess, Mobimar, Wind Servant and Houlder TAS and not only do they make it safer for personnel to transfer but the transfer can often take place in high sea conditions. This is in part due to larger vessels incorporating the access systems. There is a limit to the force a WTG can withstand and larger vessels with a larger bollard pull would require a substantially additional structural performance from the foundations and tower of the WTG.

Current operating vessels are already exceeding the design limits of WTG foundations and towers; increasing these limits may not yield a cost reduction.

Motion compensating telescopic gangways, made from lightweight aluminium, linking the vessel to the turbine platform, can have closed roofs to protect personnel from falling objects such as ice and can enable easy transport of parts and equipment from the WFSV to the WTG, with wheeled trolleys or pallet carriers.

Despite the benefits of a motion compensating telescopic gangway, there are deficiencies that make them slow to be implemented as best practice. The gangways require a large amount of deck area, they reduce the WFSPs cargo capacity, and the capital cost of the equipment and installation can be high. Despite this there are further systems in development and with the access issue of the future OWF becoming more immediate the use of these access systems is likely to increase.

## F.4 Useful links to service vessels

http://www.bmtng.com/design-portfolio/turbine-access-system/

http://www.mobimar.com/

http://www.austal.com/

http://www.adhocmarinedesigns.co.uk/windfarms/

http://dbbjackup.editionmanager.com/wp-content/uploads/2014/06/dbb-wind-server-rev2-2014.pdf

http://www.windpoweroffshore.com/article/1214096/getting-technicians-far-shore-wind-farms

http://www.windpowermonthly.com/article/1291038/vessels---access-z---maritime-guide-offshore-wind

http://www.renewableenergyworld.com/rea/news/article/2013/08/a-bigger-boat-offshore-wind-service-vessels-grow-up?page=2

http://www.4coffshore.com/windfarms/two-more-ctruk-workboats-for-offshore-turbine-services-aid539.html

http://www.4coffshore.com/windfarms/wind-farm-service-vessels-an-overview-aid246.html

http://publications.lib.chalmers.se/publication/174318-on-maintenance-optimization-for-offshore-wind-farms

http://www.diva-portal.org/smash/record.jsf?pid=diva2:626529

ftp://130.112.2.101/pub/www/library/report/2013/m13044.pdf

http://www.diva-portal.org/smash/record.jsf?pid=diva2:685788

http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1786757

http://appliedmechanicsreviews.asmedigitalcollection.asme.org/article.aspx?articleid=1398327

http://rd.springer.com/chapter/10.1007/978-1-84628-126-6_1#page-1

http://rd.springer.com/chapter/10.1007/978-1-4614-0869-7_6#page-1

http://www.sciencedirect.com/science/article/pii/S0951832012001585

ftp://130.112.2.101/pub/www/library/report/2011/m11103.pdf

http://www.sintef.no/uploadpages/330498/Sperstad_DeepWind_access_draft_v_2014-01-20.pdf

http://www.davidpublishing.com/davidpublishing/Upfile/12/23/2013/2013122381913601.pdf

http://www.sintef.no/uploadpages/330498/Dinwoodie_etal_reference_cases_draft_v_2014-02-06.pdf

http://sintef.se/project/Nowitech/Publikasjoner/HSE%20challenges%20related%20to%20offshore%20renewable%20energy.pdf

http://www.sciencedirect.com/science/article/pii/S0960148112006660

http://www.windenergy.citg.tudelft.nl/fileadmin/Faculteit/LR/Organisatie/Afdelingen_en_Leerstoelen/Afdeling_AEWE/Wind_Energy/Research/Publications/Publications_2001/doc/Bussel_State_of_the_art_owec2001_ca.pdf

http://ocw.tudelft.nl/fileadmin/ocw/courses/OffshoreWindFarmEnergy/res00055/MAREC_2001_OM_Paper.pdf

http://www.sciencedirect.com/science/article/pii/S0964569108001129

http://www.sciencedirect.com/science/article/pii/S1471084607700628

http://ac.els-cdn.com/S1471084607700628/1-s2.0-S1471084607700628-main.pdf?_tid=a8bd4a94-1d71-11e4-903f-00000aab0f6c&acdnat=1407333652_8640d0581318830459ca51c1ad084fc0

http://www.danishyachts.com/range-products/swath-25m-2/

http://www.dalbyoffshore.com/

http://www.gl-group.com/pdf/GL_Shiptype_Offshore_Service_Vessel.pdf

http://www.slideshare.net/VIKINGlifesavingequipment/development-of-regulations-for-the-offshore-wind-energy-sector-crew-transfer-large-wind-farm-ships-and-the-imo

# Appendix G: Operation and Management of Sheringham Shoal Offshore Wind Farm

## G.1 Introduction

This report summarises a 12 month period of an operations and maintenance (O&M) campaign at the Sheringham Shoal Wind Farm., from June 2013 to June 2014.

“To ensure that the wind turbines operate to their maximum capacity, an effective programme of O&M is needed, with wind turbine engineers and technicians traveling to and from the wind farm every day.” [26]

## G.2 Vessel Usage Analysis

Two sources were used for the collection of vessel usage data: Statoil’s own internally generated data where their monthly reports were primarily used (Fig. G.1), however, these reports were not explicitly created to convey data associated with vessel usage at the Sheringham Shoal wind farm, hence the data is supplemented with information from the 4C Offshore website (Fig. G.2) and marine traffic. [27-9]

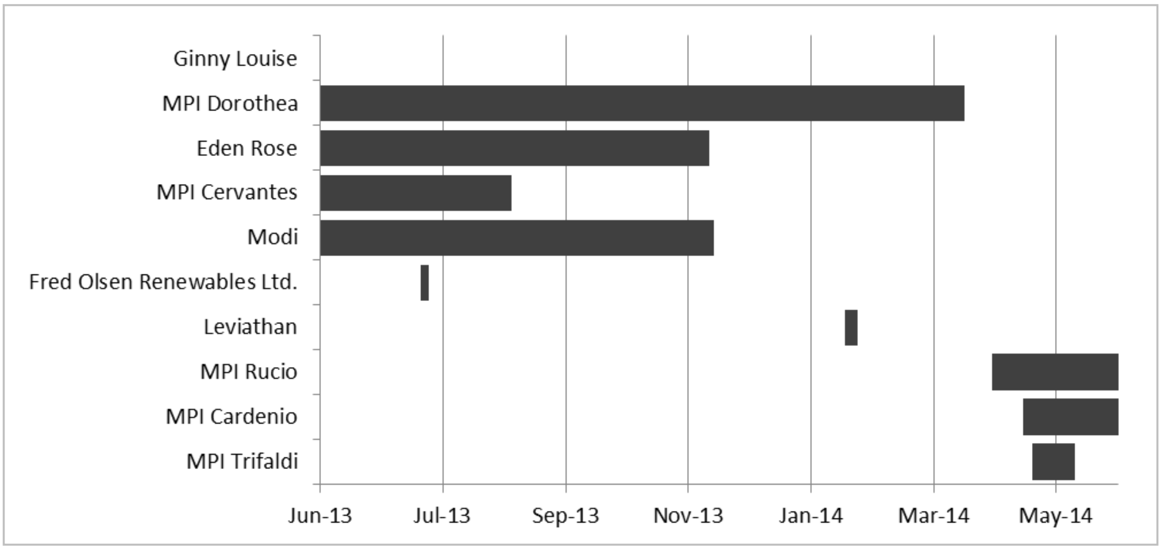


**Figure G.1** Vessel usage as garnered from Statoil’s internal monthly reports

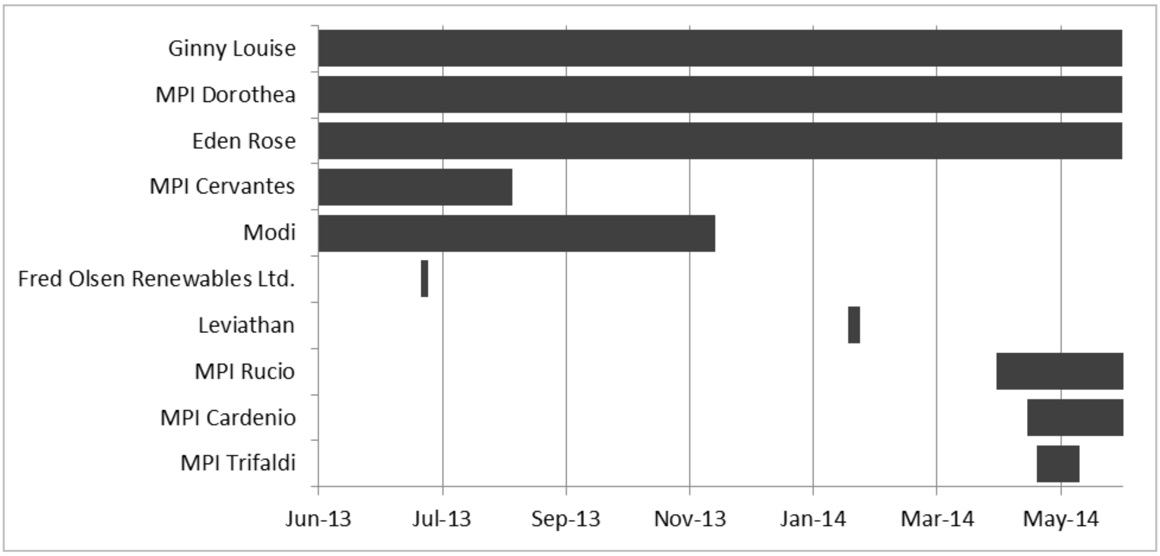


**Figure G.2** Vessel usage as garnered from Statoil’s internal monthly reports and the 4C Offshore website

## G.3 Wind Turbine Generator O&M and Personnel Data

Vessel usage is only part of the O&M scheme, the breakdown of personnel, teams and turbine downtime are presented below and show trends of increasing averaged data.

The first chart (Fig. G.3), whilst providing detailed information on the service personnel and WTGs broken, it is difficult to detect the trends that we are looking for in an overview. The subsequent weekly and monthly charts (Fig. G.4 and G.5, respectively), make any trends more easily noticeable, while an overview of the 1st Annual Service at the Sheringham Wind Farm is found in Figure G.6.

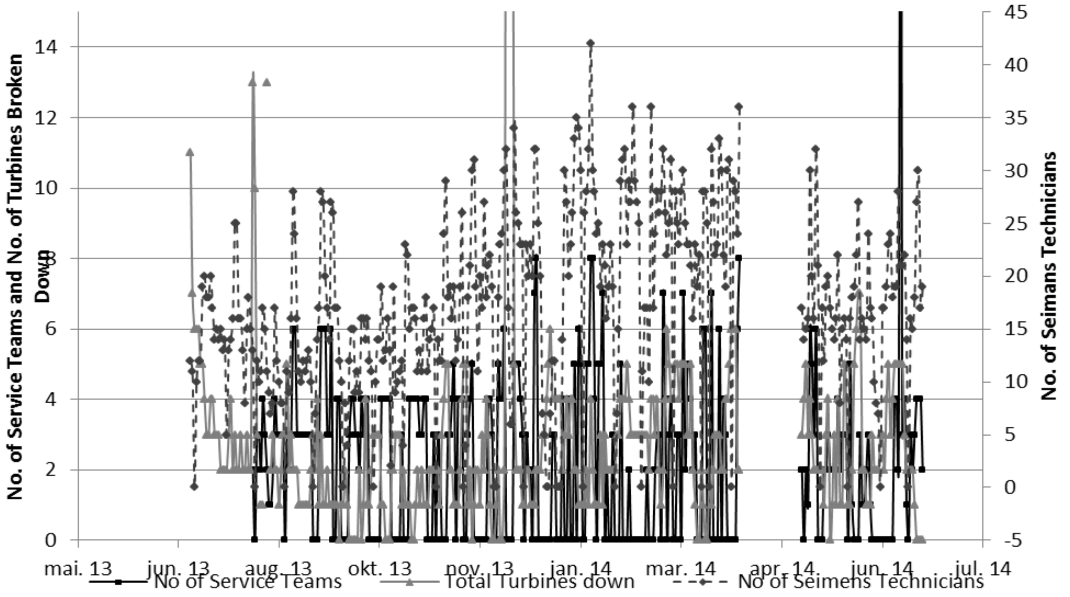


**Figure G.3** Day to day data from the Sheringham Shoal Wind Farm

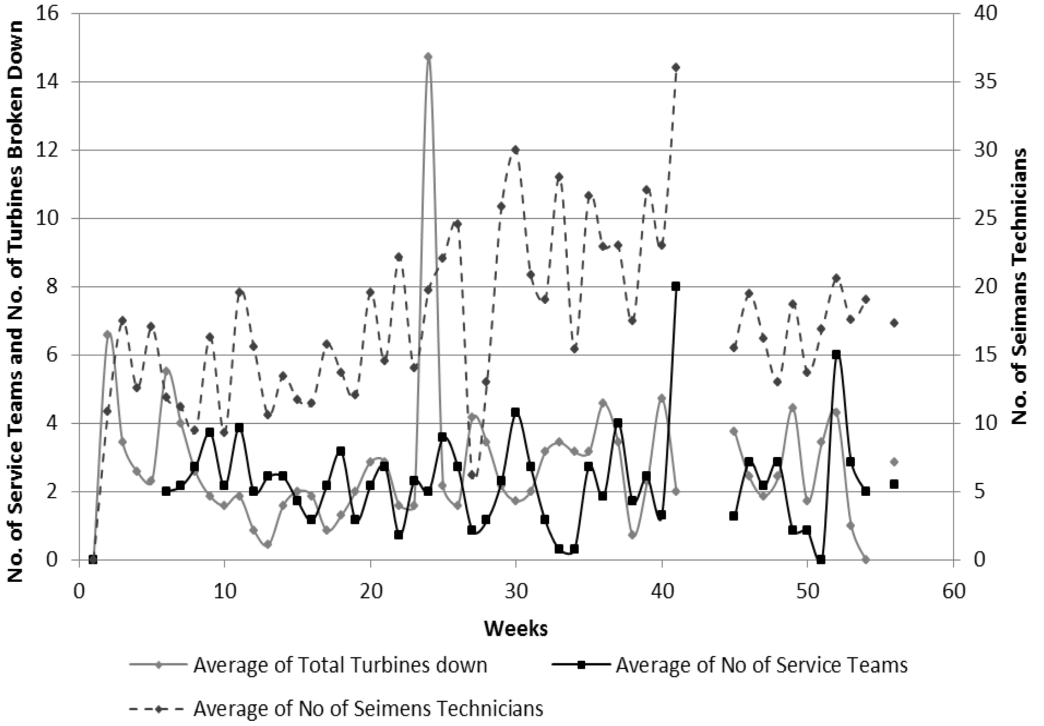


**Figure G.4** Weekly data from the Sheringham Shoal Wind Farm

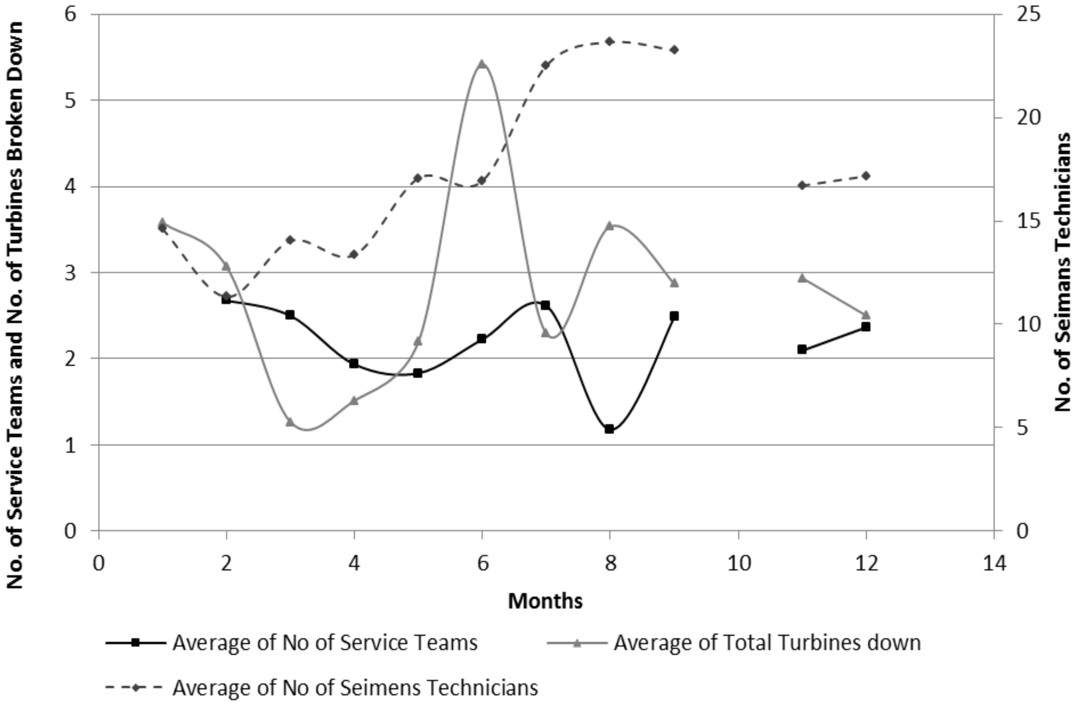


**Figure G.5** Monthly data from the Sheringham Shoal Wind Farm

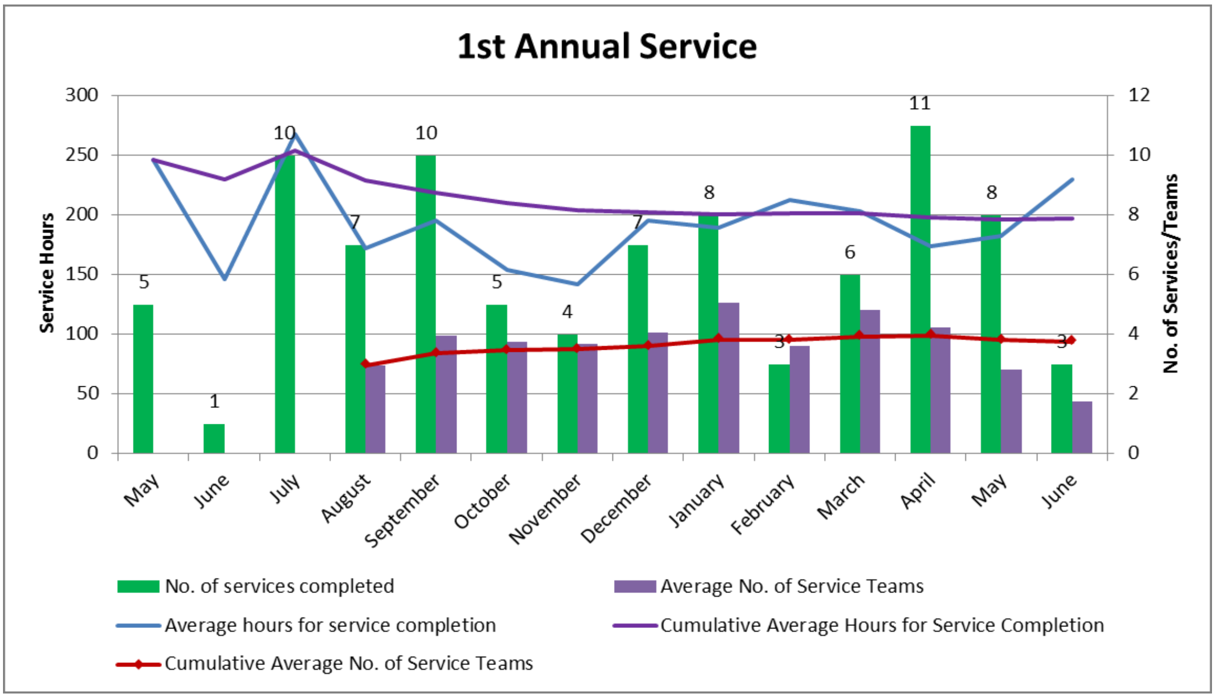


**Figure G.6** Summary of the 1st Annual Service at the Sheringham Wind Farm

## Appendix H: Assessment of Weather Windows at the North Sea Site

The yearly wind and wave climate for the North Sea Site is presented in Figure H.1. The data is from January to December of 2002 and there is a data point for every hour of the year. On the wave height graph a horizontal line is placed at 1.5m to give an indication of the current WFSV operability limit.

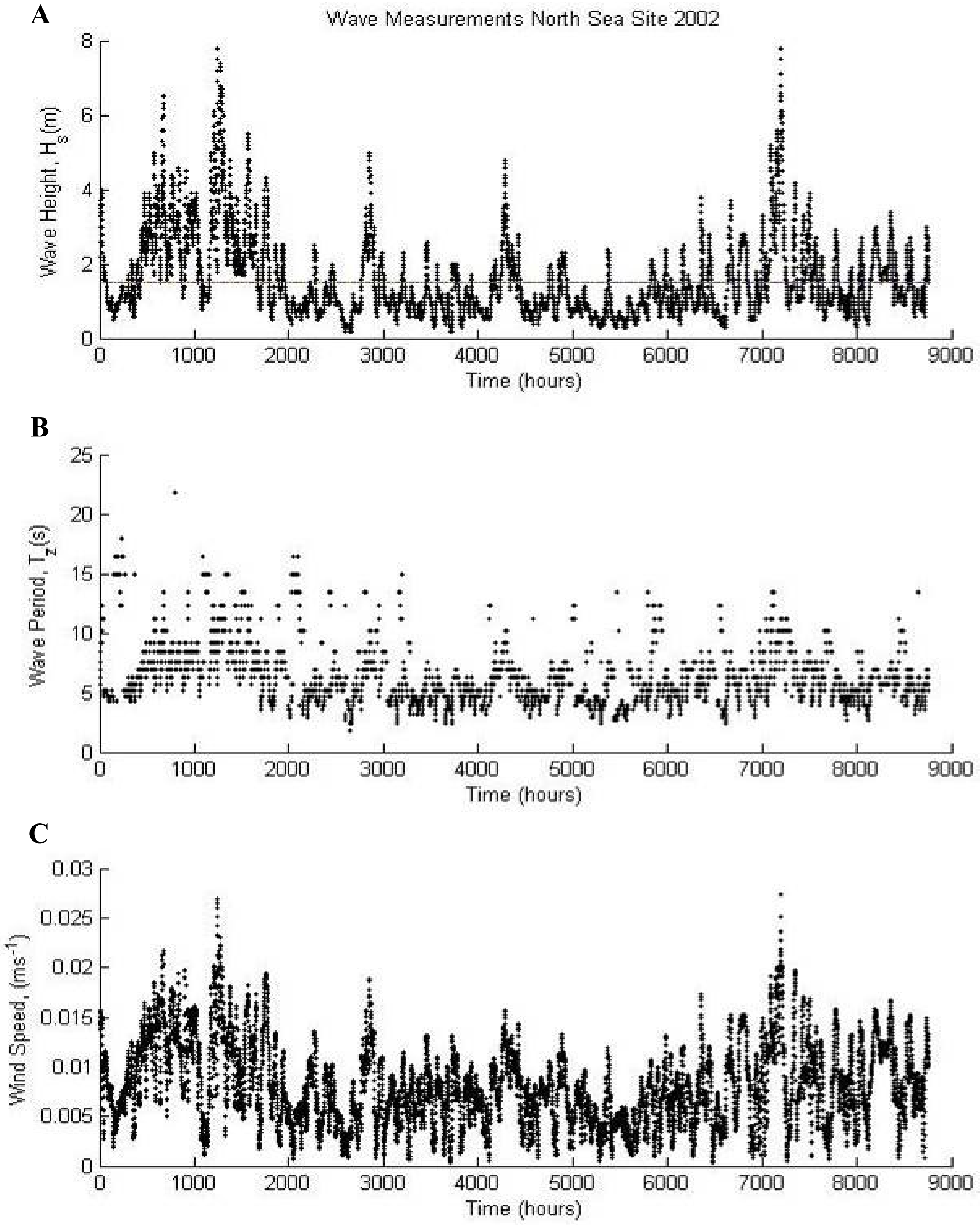


**Figure H.1** Hourly Wave Height (A), Wind Period (B) and Wind Speed (C) at the North Sea Site for year 2002

If operations commence between 6am and 12 midday, then the number of weather windows (the availability and time history of the wind and wave conditions at the site) are reduced (Table H.1 and H.2); which shows the accessibility for O&M operations over the months of the year.

**Table H.1** Number of Weather Windows/Working Days for a North Sea Site (day beginning 6:00am – 12:00pm)

| Hs limit | 1m | 1,5m | 2m | 2,5m | 3m |
|---|---|---|---|---|---|
| **January** | 7 | 13 | 18 | 22 | 26 |
| **February** | 1 | 5 | 6 | 12 | 16 |
| **March** | 11 | 15 | 19 | 24 | 26 |
| **April** | 15 | 23 | 25 | 27 | 28 |
| **May** | 14 | 25 | 26 | 30 | 31 |
| **June** | 15 | 20 | 27 | 28 | 29 |
| **July** | 17 | 24 | 29 | 31 | 31 |
| **August** | 27 | 30 | 31 | 31 | 31 |
| **September** | 11 | 24 | 27 | 29 | 30 |
| **October** | 10 | 14 | 20 | 22 | 24 |
| **November** | 9 | 19 | 22 | 26 | 28 |
| **December** | 6 | 15 | 23 | 29 | 30 |
| **Total** | **143** | **227** | **273** | **311** | **330** |

The percentage accessibility is calculated from the ratio of number of working days to number of days per year. Table H.2 gives an indication of the productivity of an O&M operation, based on different sea condition limits and months of the year.

**Table H.2** Percentage Accessibility of Weather Windows for a North Sea Site (day beginning 6:00am – 12:00pm)

| Hs limit | 1m | 1,5m | 2m | 2,5m | 3m |
|---|---|---|---|---|---|
| **January** | 23 | 42 | 58 | 71 | 84 |
| **February** | 4 | 18 | 21 | 43 | 57 |
| **March** | 35 | 48 | 61 | 77 | 84 |
| **April** | 50 | 77 | 83 | 90 | 93 |
| **May** | 47 | 83 | 87 | 100 | 103 |
| **June** | 50 | 67 | 90 | 93 | 97 |
| **July** | 55 | 77 | 94 | 100 | 100 |
| **August** | 87 | 97 | 100 | 100 | 100 |
| **September** | 37 | 80 | 90 | 97 | 100 |
| **October** | 32 | 45 | 65 | 71 | 77 |
| **November** | 30 | 63 | 73 | 87 | 93 |
| **December** | 19 | 48 | 74 | 94 | 97 |
| **Total** | **39** | **62** | **75** | **85** | **90** |

The O&M work requirements for a potential OWF in the North Sea site study case is 1760 person-days per year. The OWF is found 100km offshore and as the maximum cruising speed of the current WFSVs is 25knots or 46.3km/hr, hence a 2hrs and 10 minutes trip will be required for transport. If some improvements in vessel speed are allowed, a 4 hour round trip to the OWF can be achieved. 1760 person-days working 8hrs per day is 15680hrs or 3920 total trips to the OWF. Dividing 3920 Total trips by the number of working days results in the number of technicians required, this is presented in Table H.3. In practice though, such a perfect set-up is not possible due to a number of factors such as the unpredictability of unplanned maintenance and the variability of wind and wave conditions resulting in a less efficient O&M campaign.

**Table H.3** Number of technicians required according to wave height and working day availability

| **Significant Wave Height, $H_s$** (m) | **No. of Working Days** | **No of Technicians Required** |
|---|---|---|
| 1 | 140 | 26 |
| 1,5 | 228 | 16 |
| 2 | 273 | 12 |
| 2,5 | 313 | 12 |
| 3 | 330 | 10 |

# Appendix I: Poster "A CASE STUDY OF MULTI-USE OFFSHORE PLATFORMS "

## Poster no. 616, EWEA2013, Vienna, Austria, 4-7 February, 2013

PO.
616

# A CASE STUDY OF MULTI-USE OFFSHORE PLATFORMS

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I. Ostvik (NorWind Installer, Norway)
Ø. Bergh (Institute of Marine Research, Norway)
J. V. Kringelum (DONG Energy, Denmark)

## Abstract

This work represents a theoretical case study of a multi-use platform (MUP). It is part of an on-going EU funded collaborative research project (MERMAID). European offshore wind farms aim to approach a capacity of 150 GW by 2030. Such ambition will require a seabed area of approximate 4000 to 5000 km² but with a small physical footprint (including cables) of 300 to 400 km². Theoretically, the remaining space can be used for other purposes such as aquaculture and wave energy. Accordingly, MERMAID aims at the multi-use of ocean space for energy extraction, aquaculture and platform related transport. This case study presents an innovative proof of concept to integrate aquaculture and wave energy technology at offshore wind farms. The proposed MUP case includes marine energy extraction (1000 MW wind farm plus a wave farm), an aquaculture farm, and the installation, operation and maintenance technologies for the MUP. The synergies and the disadvantages of the MUP compared to the offshore wind farm will be evaluated during the installation, operation, and maintenance phases.

## Objectives

The proposed MUP case has, as its goal, the improvement of offshore wind economics and the reduction of conflicts with other maritime users. Accordingly, this case study encompasses the following four aspects:

- Installation, operation and maintenance of 100 units of future large 10 MW wind turbine.
- Innovative integration of aquaculture and wave energy technology at offshore wind farms.
- Installation, operation and maintenance solutions for MUP.
- The synergies and the disadvantages of the MUP compared to just an offshore wind farm.

## The wind farm integration with aquaculture farm

One layout of the proposed 1000 MW wind farm is shown in Fig. 1 and it has two offshore substations and 100 fixed foundation 10 MW wind turbine units. The upper limit of the future large 10 MW wind turbine unit is chosen for the installation evaluation. The wind farm occupies an area of 138 km². As shown in Fig. 1, a total of 72 large areas contained within the offshore wind farm area have the potential to create high value aquaculture production, including utilization for mussel and seaweed and salmon production at deep water site.

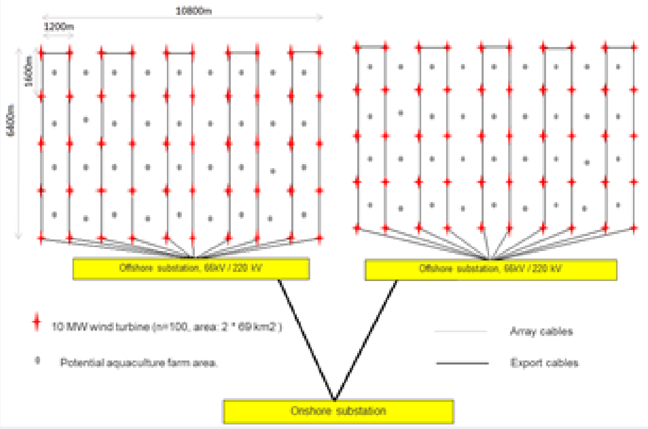

Fig. 1. Potential aquaculture areas within the 1000 MW offshore wind farm

## Highlights of the MUP case study

First, the MUP case study plans to investigate the installation of the future large 10 MW wind turbine unit. A new type of installation vessel, shown in Fig. 2, is selected as an example to conduct the installation of 10 MW wind turbine foundations. The installation is performed in two operations: pre-piling and jacket installation. Standard jack-up vessels are utilized to simulate the turbine installation operations.

Fig. 2 A new installation vessel for 10 MW wind turbine foundation installation (courtesy NorWind / Ulstein)

Second, the aquaculture application includes two scenarios. In the partially integrated installation, the aquaculture farm is adjacent to or surrounds the wind farm. In the fully integrated installation, the aquaculture farm is contained within the wind farm area. The offshore wind farms may provide space and physical structures to support establishment of offshore environments for aquaculture.

Third, the synergies and disadvantages of a 1000 MW wind farm integration with aquaculture farms will be evaluated with regard to the following three criteria: yield, cost and impact on the marine environment. The cost synergy includes the sharing of the infrastructure, installation, operation and staff accommodation during installation phase and also during the operation and maintenance phase. The cost also accounts for potential conflict risks from the system integration.

The MUP case will be eventually expanded to also include wave energy.

## Conclusions

This on-going study case proposed an innovative integration of aquaculture and wave energy technology at offshore wind farms. The cost synergy of the proposed MUP has the potential to improve offshore wind power economics by the yield increase from the aquaculture productions and the wave energy. Furthermore, there is a cost reduction by sharing the infrastructures together with the installation, operation and maintenance. However, offshore aquaculture and wave energy technology are both in experimental stages; many challenges regarding the integration with offshore wind farm structures are still unresolved and under investigation.

The funding from EU FP7 grant 288710 and the contributions from the participators of MERMAID project are acknowledged.

EWEA 2013, Vienna, Austria: Europe's Premier Wind Energy Event

## Appendix J: Oral presentation “Synergies with Other Maritime Technologies”

### EWEA2013 Offshore Wind, Frankfurt, Germany, 19 to 20 November, 2013

Track: Industrialising the supply chain, Section: Synergies with other maritime technologies
19 to 21 November, 2013
Frankfurt, Germany

**Synergy and disadvantage:**
**Offshore wind farm integration with aquaculture farm and with wave farm**

**Preliminary case study results from EU FP7 Mermaid project**

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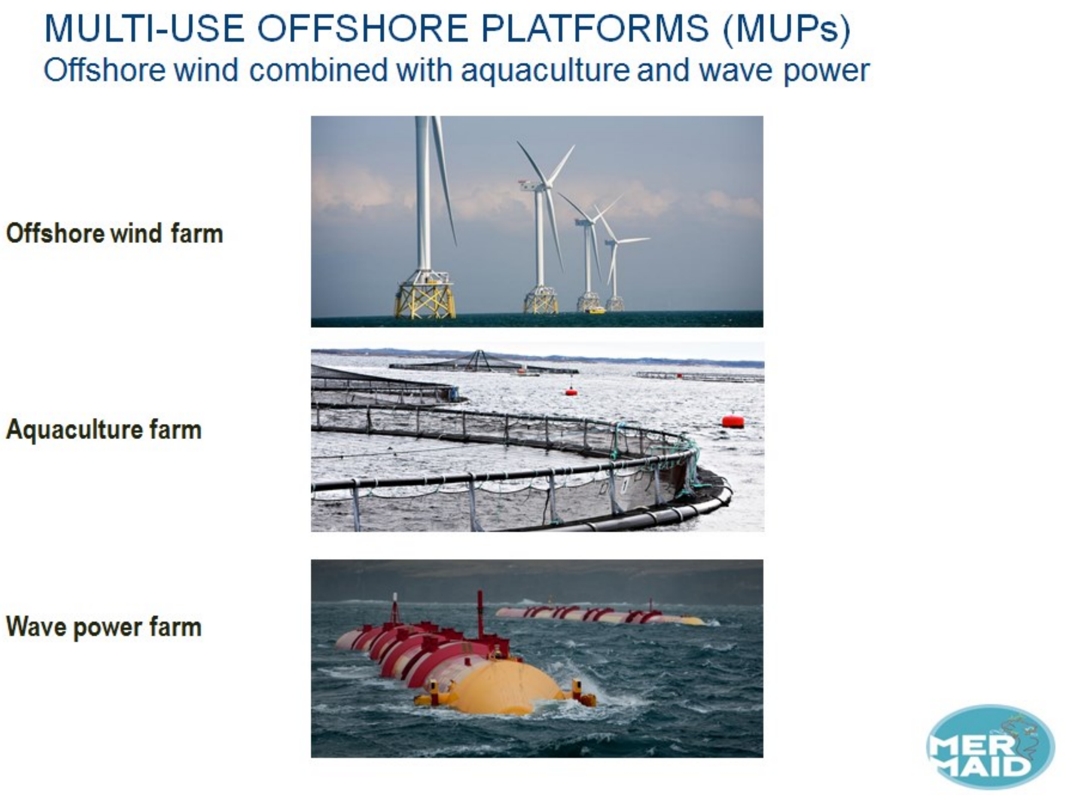
J. V. Kringelum (DONG Energy, Denmark), J. Schouten (Deltares, the Netherlands)
P. Koundouri, O.G. Dávila (Athens University of Economics and Business-Research Centre, Greece)
C. Jimenez (EEWRC, The Cyprus Institute, Cyprus), G. Bellotti (University of Rome3, Italy)



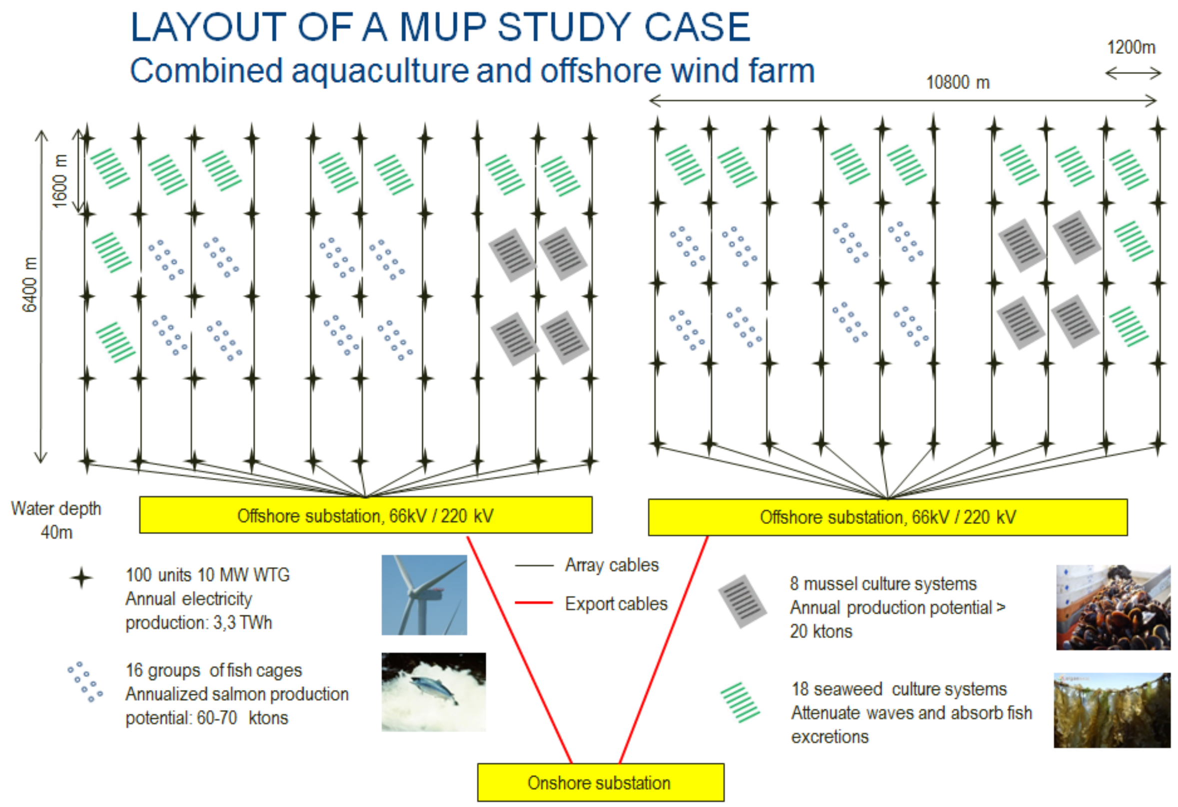
## MULTI-USE OFFSHORE PLATFORMS (MUPs)

Offshore wind combined with aquaculture and wave power

**Offshore wind farm**

**Aquaculture farm**

**Wave power farm**



## LAYOUT OF A MUP STUDY CASE

Combined aquaculture and offshore wind farm

Offshore substation, 66kV / 220 kV

Offshore substation, 66kV / 220 kV

Onshore substation

✦ 100 units 10 MW WTG Annual electricity production: 3,3 TWh

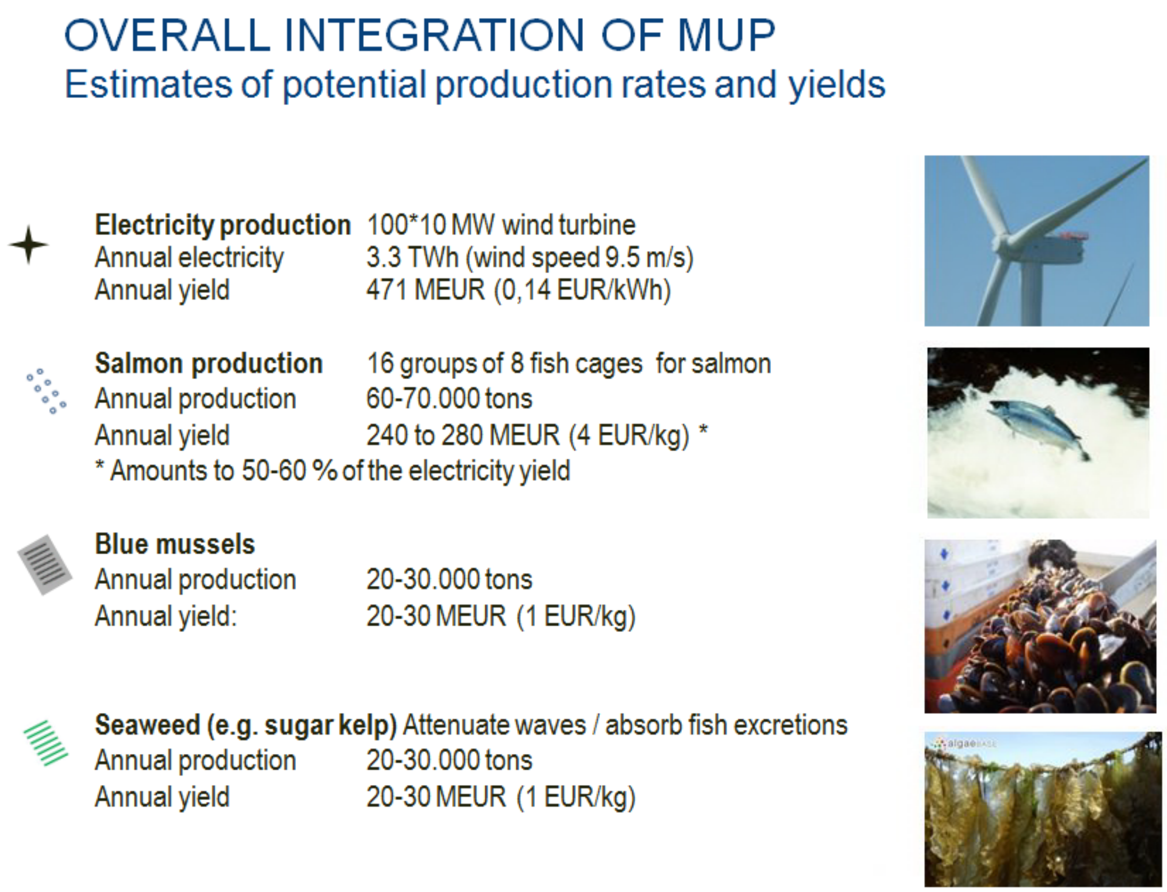
⁘ 16 groups of fish cages Annualized salmon production potential: 60-70 ktons

— Array cables

— Export cables

▤ 8 mussel culture systems Annual production potential > 20 ktons

▨ 18 seaweed culture systems Attenuate waves and absorb fish excretions



# OVERALL INTEGRATION OF MUP

## Estimates of potential production rates and yields

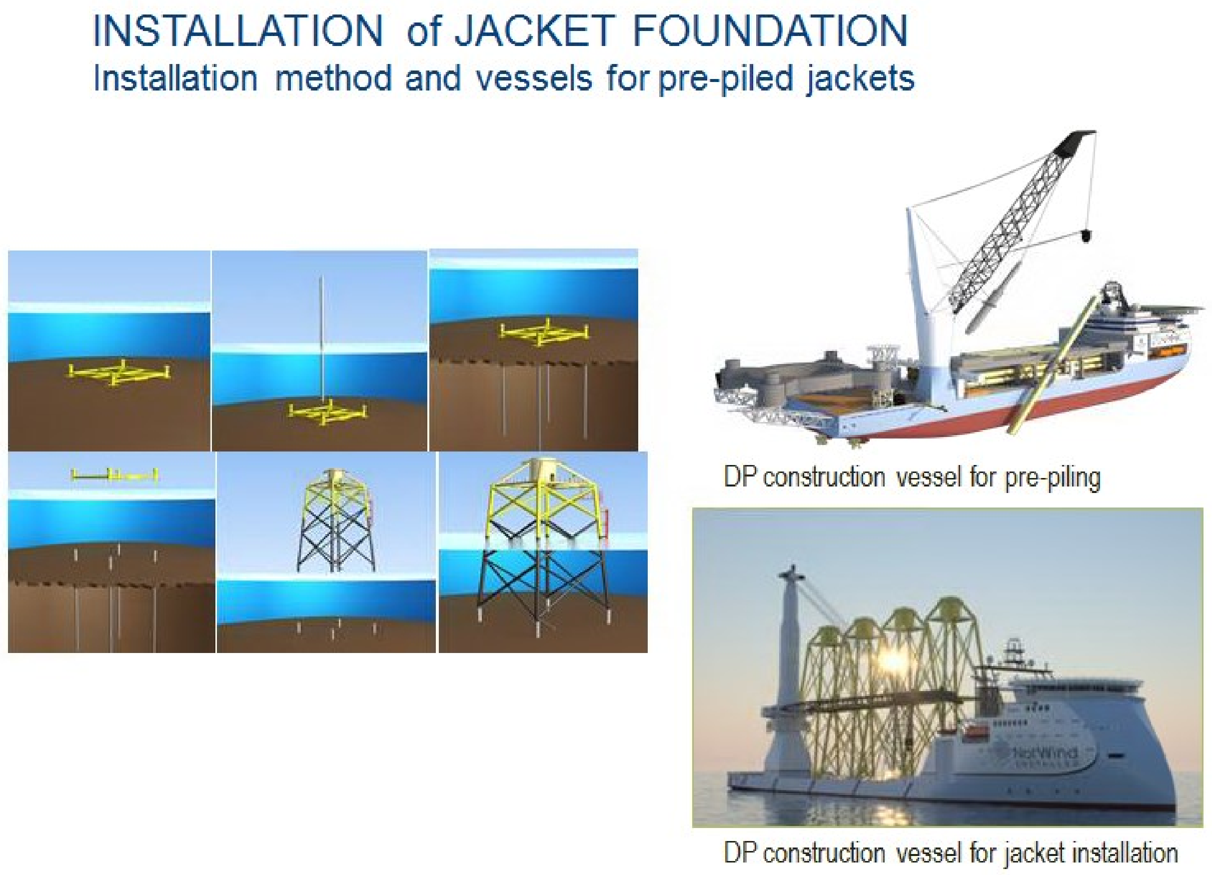
| **Electricity production** | 100*10 MW wind turbine |
|---|---|
| Annual electricity | 3.3 TWh (wind speed 9.5 m/s) |
| Annual yield | 471 MEUR (0,14 EUR/kWh) |

| **Salmon production** | 16 groups of 8 fish cages for salmon |
|---|---|
| Annual production | 60-70.000 tons |
| Annual yield | 240 to 280 MEUR (4 EUR/kg) * |

* Amounts to 50-60 % of the electricity yield

| **Blue mussels** | |
|---|---|
| Annual production | 20-30.000 tons |
| Annual yield: | 20-30 MEUR (1 EUR/kg) |

| **Seaweed (e.g. sugar kelp)** | Attenuate waves / absorb fish excretions |
|---|---|
| Annual production | 20-30.000 tons |
| Annual yield | 20-30 MEUR (1 EUR/kg) |

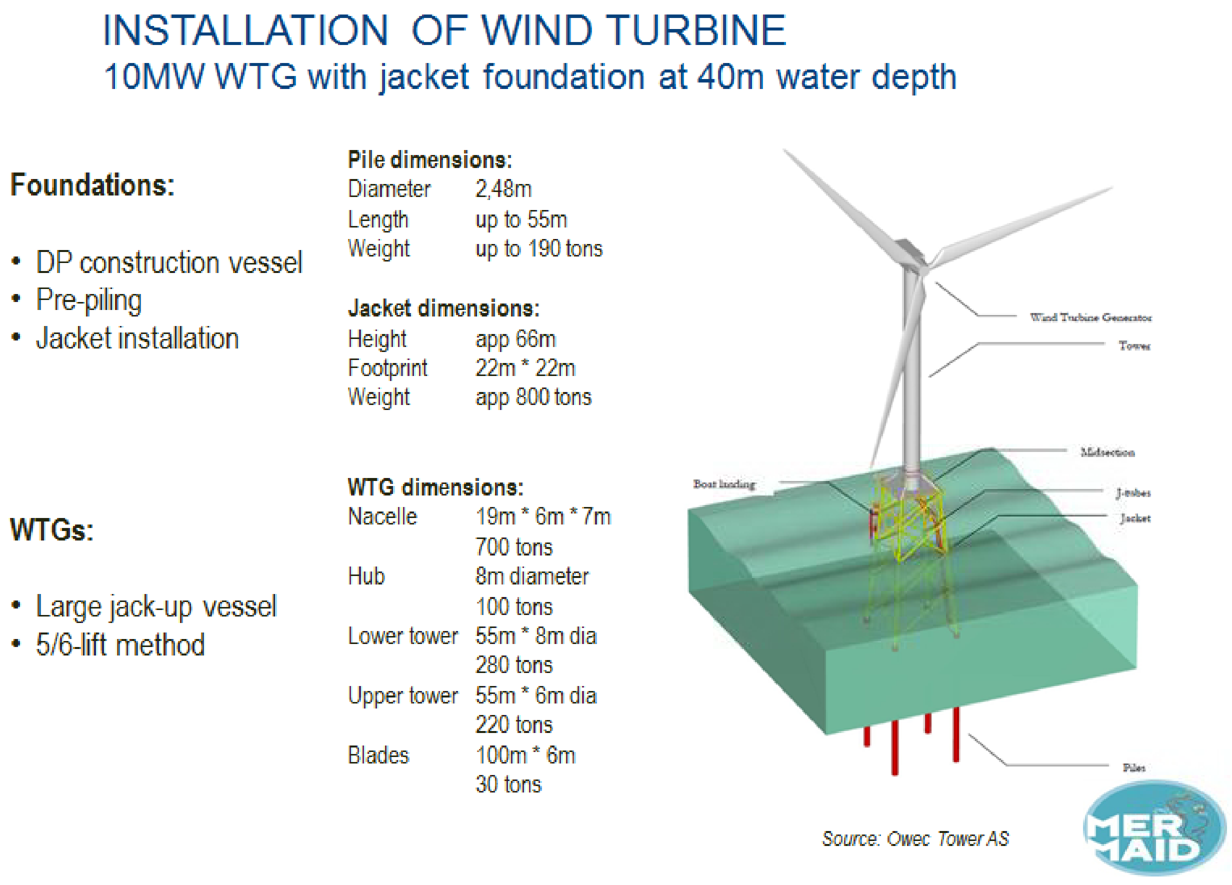


## INSTALLATION of JACKET FOUNDATION

### Installation method and vessels for pre-piled jackets

DP construction vessel for pre-piling

DP construction vessel for jacket installation



## INSTALLATION OF WIND TURBINE

### 10MW WTG with jacket foundation at 40m water depth

**Foundations:**

- DP construction vessel
- Pre-piling
- Jacket installation

**Pile dimensions:**

| | |
|---|---|
| Diameter | 2,48m |
| Length | up to 55m |
| Weight | up to 190 tons |

**Jacket dimensions:**

| | |
|---|---|
| Height | app 66m |
| Footprint | 22m * 22m |
| Weight | app 800 tons |

**WTGs:**

- Large jack-up vessel
- 5/6-lift method

**WTG dimensions:**

| | |
|---|---|
| Nacelle | 19m * 6m * 7m<br>700 tons |
| Hub | 8m diameter<br>100 tons |
| Lower tower | 55m * 8m dia<br>280 tons |
| Upper tower | 55m * 6m dia<br>220 tons |
| Blades | 100m * 6m<br>30 tons |

Source: Owec Tower AS

## INSTALLATION:10MW WIND TURBINE

**Jack-up vessel with four lifts:**

- Lower tower: 55m * 8m dia, 280 tons
- Upper tower: 55m * 6m dia, 220 tons
- Nacelle:19m * 6m * 7m, 700 tons
- Rotor: 200m, 190 tons (3 blades and hub assembled on the vessel)


Tower installation in two lifts


A large jack-up with high loading capacity

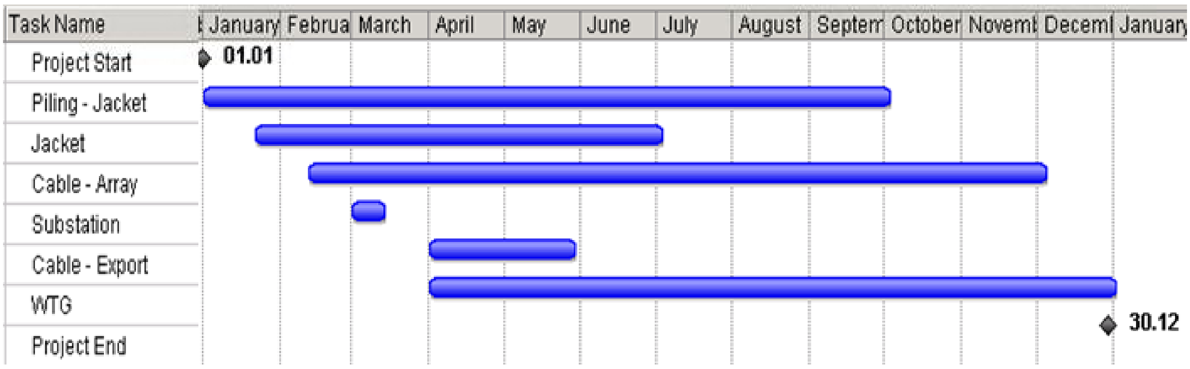

Assemble rotor on the vessel


Install rotor

## INSTALLATION 1000MW OFFSHORE WIND FARM

**Proposed time table:**

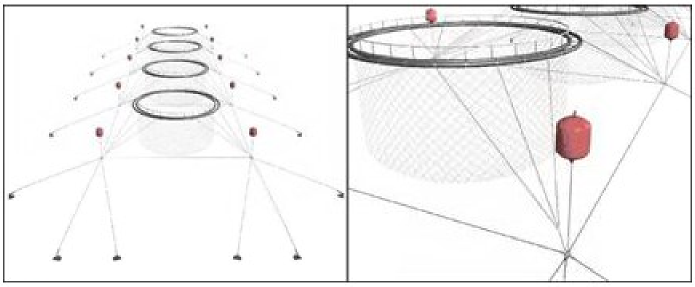
- Several installation operations run parallel with each other
- Goal: Installation a 1000MW wind farm in one year!



## AQUACULTURE FARM
### Floating and submersible fish cages

A group of 8 fish cages:
- Fish cages' weight: 8 * 46 tons
- Mooring system: 75 tons

Installation:
- Cage assemble onshore
- Mooring system offshore:
  - A work boat with a deck area: 6 x 10 $m^2$ & a crane lifting capable: 6 tons
  - 2 months for a team of 2 divers & a crew (4-5 people)



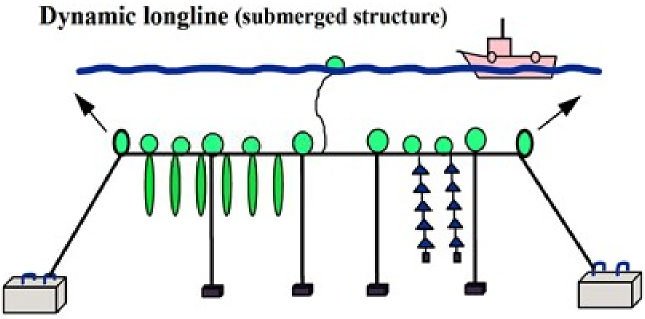
Operation under offshore conditions

Cage assemble onshore

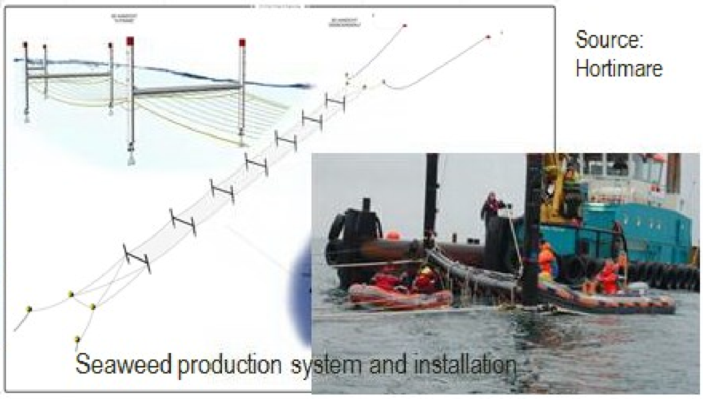
## AQUACULTURE FAMM
### Mussel and seaweed systems

**Mussel production system:**
- Production lines (drops): 20 m
- Submerged (5-7m below MSL) to avoid of loss of mussels during storms

**Seaweed production system**:
- Attenuate waves and absorb fish excretions
- H structure



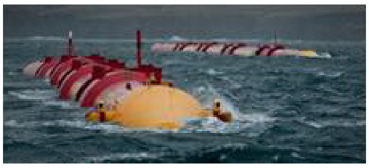
**Dynamic longline** (submerged structure)



Seaweed production system and installation

Source: Hortimare

# INTEGRATION OF WIND AND WAVE

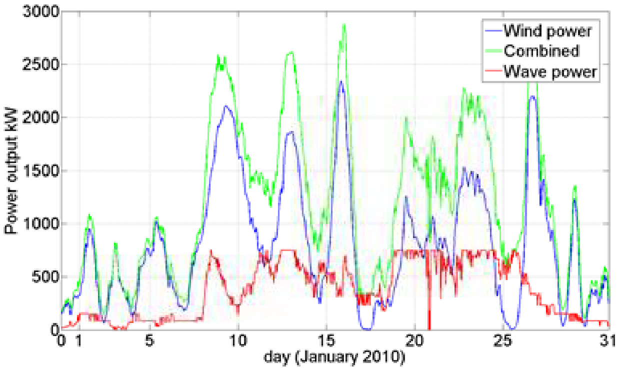


**Yield synergies:**

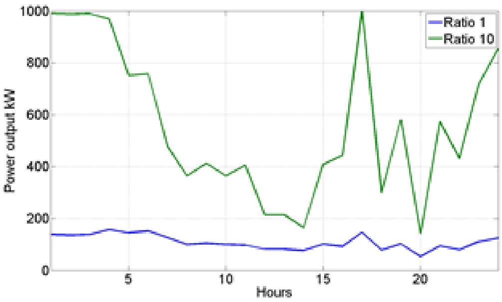
- Increase the electrical power output
- Potential to give a more stable power output than from the wind farm alone
    - ➢ The significant wave power capacity is required

**Structure synergy:**

- ➢ The wave structures have potential to reduce the loads on the wind turbine foundations



Power output from the wind turbine and wave device



Ratio: wind power capacity / wave power capacity

# SUMMARY MUTI-USE PLATFORM

## Synergies and disadvantages

**Increase yields:**

- One study case: aquaculture yield: 50-60% of electricity yield
    - ➢ High quality sea foods
- Wave power integration: more /higher quality electricity output

**Cost:**

- Sharing of the infrastructures, installations and services
- Potential joint technology developments
- Costs of aquaculture and wave power facilities

**Impact on the environment:**

- Ocean space sharing: turn the conflicts into co-operation
- Offshore aquaculture: reduce pollution in (populated) coastal area

**Disadvantages:**

- Offshore wind farm:
    - ➢ Impacts of extra marine growth on offshore wind structures due to aquaculture
    - ➢ Risks of installation conflicts and daily aquaculture O&M activities within the offshore wind farm
- Aquaculture farm: Effects from offshore wind turbines, e.g. noise
- Licensing issues may arise

## References

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