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Master Thesis

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Abstract

This report describes the computations that have been made to simulate the O&M cost for a generic floating offshore wind farm. The aim of this paper is to investigate if the floating foundation technology offers new approaches for the way offshore wind power plants are operated and maintained. The possibility to return the semi-submersible wind turbine to shore, allows that maintenance activities could be carried out near to shore (for example in a dry dock) with fewer restrictions and lower cost. The point of interest therefore is, to what extent it is technical and economical feasible to perform “offshore” maintenance in comparison with “onshore” maintenance for which the floating platform needs to be repositioned. This was studied by comparing the cost for each O&M strategy. Weather restrictions, distance to shore and the technology readiness level influence both concepts. In general, it can be concluded that with the current technology level, returning a semi-submersible floating wind turbine for scheduled maintenance campaigns on a regular basis is not an economical and technical feasible approach. Keeping in mind, that the floating wind turbine technology is still in the prototype and pre-commercial phase, this also concludes that there is still large potential for improvement.

Keywords: Floating Wind Turbines, Operation & Maintenance, Marine Operations

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For the time of the thesis, I had the great pleasure to share the basement study catacomb (Risk Room) with my fellow master students from Greece, Germany and Korea. You made this period and the lunch breaks very memorable.

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List of Abbreviations

A&R	Abandonment and recovery
AHTS	Anchor handling tug supply
BL	Boat landing
BOP	Balance of plant
CAPEX	Capital expenditures
COE	Cost of energy
CRI	Commercial readiness index
CTV	Crew transfer vessel
DNV	Det Norske Veritas
DP	Dynamically positioned
FWTU	Floating wind turbine unit
GL	Germanischer Lloyd
GW	Gigawatt
HAV	Anchor-handling vessel
H_{m0}	Significant wave height
HSE	Health, safety and environment
HVDC	High-voltage direct current
IMO	International maritime organisation
JIP	Joint industry project
LPC	Levelized production cost
MTTR	Mean time to repair
MW	Megawatt
NAWT	Net available working time
NDT	Non-destructive testing
NDT	Non-destructive testing
NM	Nautical mile
O&G	Oil and Gas
O&M	Operation and maintenance
OEM	Original equipment manufacturer
OSV	Offshore support vessel
PPI	Principle Power Incorporated
PT	Personal transfer
SM	Scheduled maintenance
T&I	Transport and installation
TI&M	Transport, installation and maintenance
TLP	Tension leg platform
TRL	Technology readiness level
W2W	Walk to work vessel
WBS	Work breakdown structure
WTG	Wind turbine generator

Chapter 1

1 Introduction

The first chapter of this report presents an overview of the offshore wind energy topic, relevance of deep sea application and the research question. The following chapters are devoted to:

Chapter 2:	A detailed overview of offshore wind energy, all major components in a wind farm, floating substructure technology and operation & maintenance concepts as well as influencing factors.
Chapter 3:	Theory behind modelling floating wind turbines.
Chapter 4:	Input parameters used in the study.
Chapter 5:	Results from the case studies performed as a part of the thesis.
Chapter 6:	Conclusions from the case studies and suggestions for further work.

1.1 Overview & Motivation

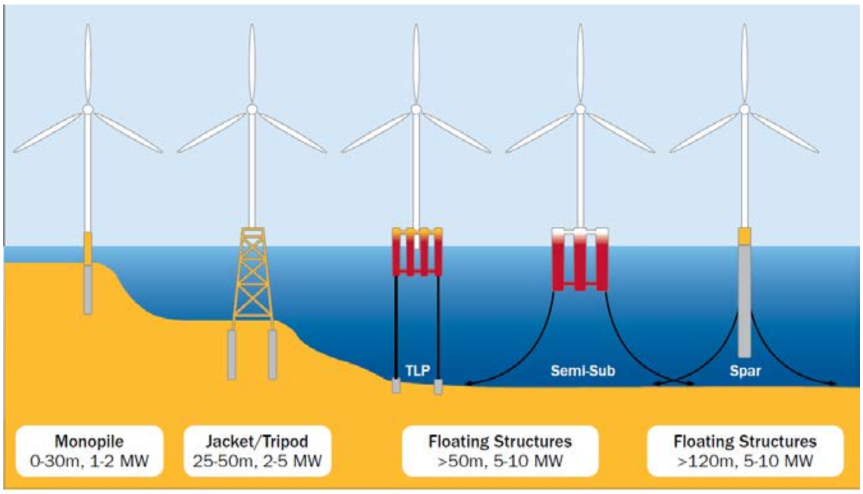
Since 2000, European offshore wind energy has developed from a frontier technology to a solid but infant industry with 3000 installed and grid connected offshore turbines, with a combined capacity of 10 GW (Ho & Mnistrova, 2015). Experience and lessons learned are increasingly improving technology levels, hence helping to lower the cost of energy (COE). Research and development demand however is still strong due to ongoing development in projects size, distance to shore and water depth.

The majority of the offshore projects (65% of the total capacity) is located in the North Sea. 19% of this capacity is installed in the Atlantic and the remaining 16% in the Baltic Sea. As the project move further away from shore, the floating wind energy technology becomes increasingly important, as current commercial foundations are limited to a maximum water depth of 50 m (Arapogianni et al., 2013).

With the exception of two (2) turbines, all of Europe's offshore wind power plants have fixed substructures. The first wind farms were erected in nearshore and shallow water areas, mainly relying on monopole and gravity based substructures. With increasing distance to shore and water depth, more and more spaced framed substructures, e.g. Tri-pile or jackets, are utilised (see Figure 1-1). By the end of 2012, two (2) full-scale prototype floating wind turbine units (FWTU) were installed and in operation. Both located in Europe, Statoil's Hywind was installed in the North Sea and the WindFloat of the cost of Portugal (Arapogianni et al., 2013).

- Hywind was the first large scale floating wind structure. Developed by Statoil and installed in 2009, it is the concept with the highest technology readiness level (TRL). It is a spar type substructure equipped with a standard 2.3 MW Siemens offshore turbine (Arapogianni et al., 2013). The spar buoy is a weight buoyancy stabilised slender cylindrical structure with a relatively large draft. End of 2015, Statoil announced the financial closure for a 30 MW pilot park, with five (5) floating 6 MW turbines that will be build off the Scottish coast (Slätte & Ebbesen, 2012).

- Principal Powers WindFloat was the second large scale floating system build. Installed of the Portuguese coast in 2011, energy production started in 2012. The WindFloat is a semi-submersible type floater equipped with a 2MW Vestas wind turbine. The semi-submersible is a free surface stabilised substructure with a relatively low draft. The WindFloat has closed the technology gap and has reached a similar TRL like the Hywind concept.



Source: Principle Power

Figure 1-1: Offshore wind foundations (Source: Principle Power Inc.)

As the industry matures, offshore wind power plants increase in project size (larger turbine size and numbers) and are moving further away from shore. This progress is currently limited by the availability of locations exceeding 50 m water depth, but in relatively close proximity to the shoreline (100km). The announced floating solutions have the potential to unlock vast areas no further than 100km from shore but exceeding water depth of 50 m. In Europe, this then would also allow offshore wind projects in the Atlantic and Mediterranean Sea and is most interesting for countries like Norway, Portugal, Spain and the UK (Slätte & Ebbesen, 2012).

Cost for floating and bottomed fixed substructures are not comparable since the floating technology is still in the prototype stage, but both are expected to flatten out and decrease in the upcoming years as the technology develops further. Cost reduction is an important aspect in offshore wind energy sector to further lower the cost of energy (COE). Even with a lot of technical challenges that still have to be overcome, floating structures also offer considerable advantages. Floating structures are not as site dependent, allowing much more standardized design and fabrication compared to the fixed foundations (Slätte & Ebbesen, 2012). Furthermore the shallow draft floating substructure do not require sophisticated offshore installation campaigns involving heavy lift operations, cutting overall installation cost. They can be assembled onshore, before being towed out to sea. This very feature not only minimizes installation cost but can also help to reduce operation and maintenance (O&M) cost. This report therefore aims to investigate the possible advantages that floating substructures and especially the WindFloat substructure might have in respect to O&M strategies for floating offshore wind farms.

1.2 Relevance

Floating wind energy offers significant technological advantages once it reaches full development. The technology has made significant development in the past years and will continue to do so, on the way to reach full commercial readiness. Cost reduction in the offshore wind energy industry is an important incentive in order to become a commercially viable technology. Not only is it vital that the technical development continuous, but also that a cost of energy (COE) level is reached, which makes it cost competitive to other renewable and conventional energy sources (Slätte & Ebbesen, 2012). An additional advantage the floating technology offers is, that it opens the door to vast deep-water locations that become available for offshore wind energy production, not only in Europe, but worldwide.

For larger size and far offshore bottom fixed wind farms, O&M strategies are just emerging and are in the focus of research by the industry as more parks are in the planning. The advancements in the development of floating offshore wind substructures have also led to more mature concepts and the WindFloat concepts, for example, is in the pre-commercial phase. Commercial projects can be expected within the next five (5) years (Rivals & Cermelli, 2014). Floating foundations will not only unlock vast new deep-water areas for wind energy production, they also offer new possibilities compared to the current installation, operation & maintenance methods. Floating substructures can make offshore installation involving expensive Jack-up units obsolete. The wind turbine generator (WTG) and the floating substructure can be fully assembled, commissioned and tested in a dry dock before being towed to the wind power plant.

Like fixed foundations, floating concepts will still be affected by access restrictions caused by poor weather. This is one major contributor to high O&M cost. But for major service overhauls the floating wind turbine unit (FWTU) can be towed back (LLC, January 2015 , p.4), therefore reducing the offshore workload. The question that arises is to what extend the floating technology and related 'onshore' O&M strategies are viable, and what are the limitations. Does the floating technology approach only allow for major components exchanges to be performed onshore or does it also hold for regular scheduled maintenance and inspections?

Planning for major component exchange is an important part of the O&M strategy. The early 'offshore' turbines were in reality lightly 'marinized' onshore turbines and turbine reliability has been an issue. A main contributor was major component failures like Gearbox breakdowns (Slengesol, de Miranda, Birch, Liebst, & van der Herm, 2010). This has been largely overcome in the past years, however capital component failures still need to be addressed and planned for in the early project phase in order to minimize cost of lost production after a component breakdown (2014). In this case, the floating substructure offers a huge potential to minimize cost and downtime since no Jack-Up is required. (Compared to the waiting time for a Jack-Up unit operation).

Floating substructures reduce decommissioning cost. Due to their shallow draft, floating substructures also offer a significant advantage compared to fixed foundations. According to IMO Resolution A.672 (16) and UNCLOS, Article 60 state that: "*Installations or structures which are abandoned or disused shall be removed to ensure safety of navigation and to prevent any potential effect on the marine environment ".* [1] Governments therefore require that the structures need to be decommissioned and removed after the operational period. From the operator's point of view, decommissioning activities represent a cost to be incurred in the future, while from the government perspective, decommissioning represents an uncertain event and financial risk, if the operator becomes insolvent. Consequently, the authorities demand companies to provide a financial security to help ensure decommissioning obligations are carried out after the design life of the power plant (Kaiser & Snyder, 2012).

The amount of cost for the provision for dismantling obligations so far is based on estimates and expert judgments, like stated in the White & Case Memorandum (Wagner-Cardenal, Treibmann, & Kahle, 2011) and amount roughly to around one (1) million Euro per foundation. The simplified decommissioning procedures offered by floating structures allow a verified reduction in decommissioning costs, which has a direct impact on the aval (financial guarantee). Hence, the floating wind energy technology offers further cost saving potential and improves the financeability of projects.

Floating offshore wind energy is an infant industry that can profit from the experience of the Oil & Gas (O&G) industry and change the current O&M strategies. Both industries began with land based technology and eventually moved in the marine environment (Slätte & Ebbesen, 2012). However, there are differences that also sets them apart. Compared to an O&G platform, where most maintenance activities can be performed at the premises, a wind power plant comprises a large number of singular and geographically separated structures, all difficult to access (weather restricted). This will be the same for a floating wind power plant. To perform schedule maintenance and inspection campaigns it could be an option to execute parts or a significant amount of the workload onshore. Therefore, the FWTU would be towed back to shore, where less weather restrictions hinder the duration of the service work. This may offer significant cost saving potential and is the key hypothetical assumption which will be analyzed in this paper.

Not only maintenance activities can be performed onshore. Periodical inspections of the turbine and substructure is a huge cost driving factors. Most offshore wind technologies are new and still evolving, which leads to high inspection requirements from classification societies and authorities. It involves rope access and diving operations, which are time consuming and expensive. These inspections can then also be undertaken during a major onshore service overhaul for the fraction of the cost from an offshore inspection.

Floating substructures will affect WTG design. Current offshore WTG are increasingly optimized and designed to allow an efficient installation with a Jack-Up vessel. Major components are located in the nacelle in order to reduce the number of lifts that have to be carried out. Floating structures will allow the turbine design to primarily focus on the maintainability and availability, since offshore lifting operations are no longer required. This will allow the design and placement, especially for the electrical components, to focus on the ease of maintenance and work procedure efficiency.

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[1] IMO Resolution A.672(16) Adopted on 19 October 1989

The two (2) most advanced concepts that have a full-scale prototype installed and which are currently tested are the Hywind and the WindFloat. Especially the WindFloat concept might have the potential for new approaches as to how an offshore wind farm can be operated and maintained. The WindFloat platform is a semi-submersible type substructure with a relatively low draft. Therefore, it can be manufactured and serviced in most dry-docks or harbours. Other floating wind turbine concepts like the Spar-type 'Hywind' platform do not have this advantage. With a draft of approximately 80m, those floating foundations require deep fjords or offshore assembling procedures and cannot easily be towed to a harbour.

1.3 Objectives

The primary aim is to investigate if it is technically and economically feasible to return a semi-submersible wind turbine to shore (to a dock or near shore facilities) to perform maintenance activities. Secondly, what are the related technological challenges and how would such a strategy affect the involved marine operations, technology and design (Moorings system, power cable, offshore support vessel)?

In addition, the following aspects will be investigated:

I. Do shallow draft floating substructures for offshore wind turbines offer new O&M approaches beyond onshore major component exchange?
II. How can we limit expensive offshore integration and maintenance procedures?
III. Effects on marine design and operations?
IV. How do factors like, distance to shore, lost production and metocean conditions influence this O&M approach?
V. Furthermore, this thesis tries to find a simple technique to compute rough cost estimates for O&M concepts. This is important to verify outputs from O&M simulation tools and make plausibility checks.

The overall goal is to develop a better understanding of the 'return to shore' service approach for FWTU and pinpoint improvement potential, which will support installation as well as operation and maintenance concepts for floating substructures.

Chapter 2

2 Background

2.1 Offshore wind energy overview

In this chapter, all major components and the balance of plant (BOP) of an offshore wind farm and the recent developments are briefly described. This should provide the reader with a broad picture of the status, trends and challenges of the offshore wind industry. From 2000 until 2010, the majority of offshore wind projects, which have been finalized, had an average project size of 110 MW, ranging from 25.2 to 209 MW. Average turbine size did not much increase in that period and the dominated size installed ranged from 2 to 3.6 MW mainly supplied from Siemens and Vestas. Most of the projects can be considered as near shore, with an average distance to shore of 12.5 km and an average water depth of 11m. Due to that, the prevailing foundation type utilized are the monopole and a few gravity based foundations. The near shore location of these projects made it possible to either directly connect into onshore substations, or use offshore transformer stations with a voltage step up of 132-150kV (Slengesol et al., 2010).

However, most near shore and shallow sites have been developed by now and stakeholder and environmental concerns are lower with increasing distance to shore. This results in a clear trend towards far-offshore projects. The increasing distance is affecting all major fields of the wind farm. Increasing water depth requires floating wind turbines. Larger turbines need to compensate the increased capital expenditure (CAPEX) for foundations and the grid connection. The increased remoteness sets new requirements to the power transmission technology, the logistics and installation technology, as well as operation and maintenance requirements.

2.1.1 Definition and key components

In this report, the following terms are used to describe the major components and systems of the wind farm. Following the GL Guidelines for the Certification of Offshore Wind Turbines (GL, 2012): "*the offshore wind turbine consists of the machinery or topsides structure (rotor and nacelle) and the support structure (tower, sub-structure and foundation or floating body, mooring and anchors)*" as shown in Figure 2-1 . In this report, the term turbine refers to the nacelle including the rotor. Structure or substructure refers to the whole structure (substructure and foundation) placed in the soil and water column. The generated electricity from the turbine is transported via 30-34 kV infield cable to the offshore substation. All the infield cables are bundled here and the voltage is transformed to 132-150 kV before being sent via the export cable to the grid connection point (see Figure 2-2). The on-site substation or transformer platform also offer space for living quarters and storage facilities (Slengesol et al., 2010). The offshore substation, subsea equipment, e.g. scour protection, and the cables between the wind turbines and the offshore substation are referred to as balance of plant (BOP).

2.1.2 Future wind farms

In the upcoming years, marine wind energy projects will increase in size reaching 500 MW per development and sites will be located 100 km from shore in water depth ranging from 50-150 meters or more. Deep water conditions will be predominant in future projects depending on floating foundation designs. Turbines size is also increasing, reaching 5-6 MW since more full-load hours/year are expected, and the higher energy production should compensate higher cost of energy (COE) from far-offshore locations compared to near shore sites. This also affects the grid connection and future projects will have to rely more on HVDV technology to transport the produced energy to shore (MAKE Consulting A/S, 2014).

The distance to shore and water depth will be the main technology and cost driving mechanism in this emerging industry affecting all major components and lifecycle stages.

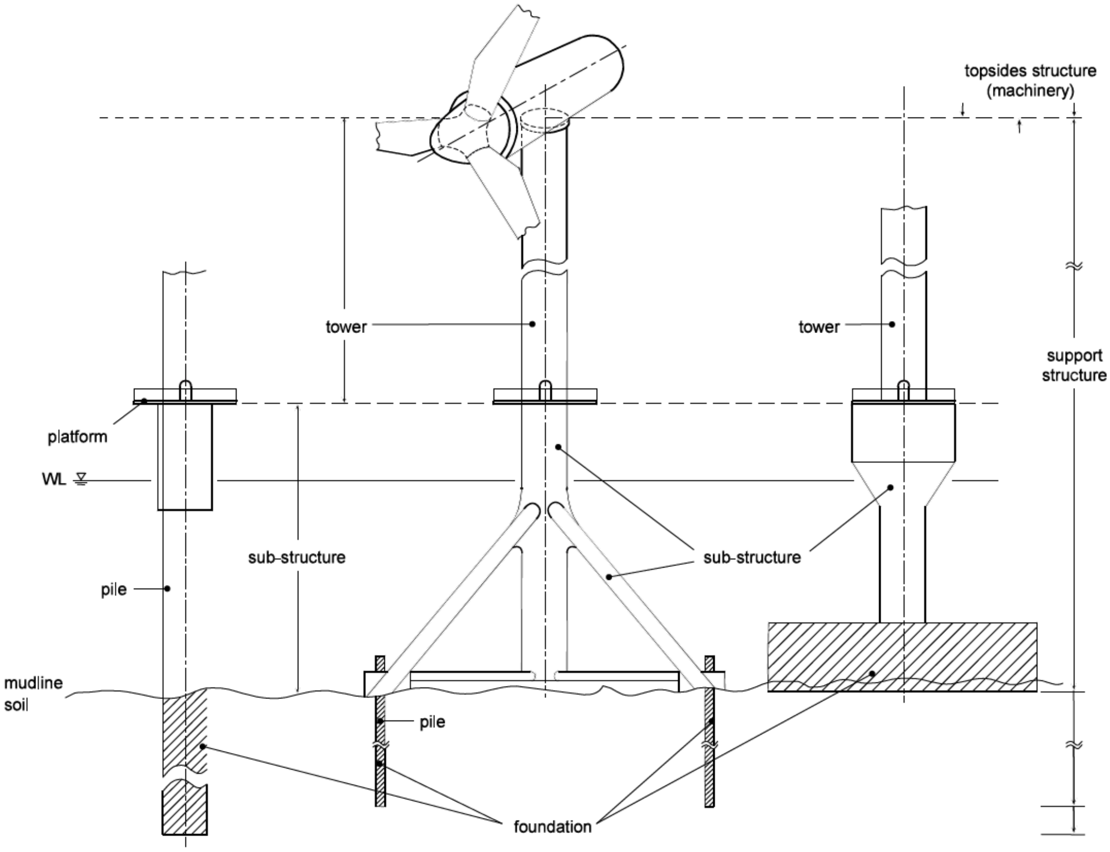

Figure 2-1: Definition of offshore wind turbine sections, source: (GL, 2012)

2.1.3 Foundation - from shallow to deep water

Monopiles and gravity-based concepts were the preferred substructure type in near-shore projects, but are neither cost competitive nor technical feasible in deep water conditions exceeding 30m of water depth (Slengesol et al., 2010). Spaced frame like the tripods, tri-piles or jacket type concepts have been developed and are increasingly used and installed for water depth between 30-50m (see also Figure 2-1). This substructure sector still faces design and installation challenges due to a lack of technical and commercial experience and many trial and error mistakes have been made. From an operational point of view, the condition monitoring aspect is the most important one to consider regarding the substructures. Periodical inspections (condition monitoring) must be performed to monitor the structural integrity throughout the lifetime of the structure. For the assessment of weld hotspots, fatigue cracks and corrosion effects, non-destructive testing (NDT) methods are applied and divers carry out the inspections. Hundred (100) and more structures will be installed in future projects. This high number of singular structures accumulates an enormous scoop of underwater inspections work, which has to be performed. This should already be taken into account already during the concept and design stage of the project to support the selection of the most suitable support structures solution aligned with the in service and monitoring concepts. The above listed circumstances speak in favor for floating structures, as they offer possibility for cost saving in many ways.

2.1.4 Turbine - from onshore to offshore

Today, onshore wind turbine generators (WTG) can be regarded as proven technology, since they experienced a strong and stable development over the last 20 years. For the offshore application, most manufacturers lightly marinized and scaled up their onshore design and the traditional three bladed turbine type is dominating the current offshore wind sector. This however, proved itself not to be enough, revealing problems in the first years of offshore operation. Many projects experienced major component failures (gearboxes, generators and transformers) resulting in poor availability and loss of production (Slengesol et al., 2010).

The offshore environment not only requires a more solid design, it also influences the accessibility and serviceability of a WTG: "*this may easily lead to an unacceptable down time level. This makes it inevitable to assess the O&M demand of an offshore wind farm in conjunction with other design parameters in order to achieve the required availability level against optimal cost expenditure*" (Van Bussel & Zaaijer, 2001). The operation and maintenance perspective must be the dominant design and decision criteria and was underestimated in past and current projects. Immature maritime adaptation, no pro-active O&M approach during the concept and design phase and restricted accessibility in many offshore projects, resulted in cost ineffective performance values in respect to O&M activities.

In order to reduce maintenance efforts, the current WTG design has to be reconsidered in terms of serviceability and its adaptation for the marine environment (Van Bussel & Zaaijer, 2001). This could comprise modular design and a reduction of components like in the Siemens 6MW direct drive technology SWT-6.0 Turbine, where the gearbox has been eliminated or more sophisticated remote control and monitoring systems.

2.1.5 Grid Connection - Infield cables, Export cables and HVDC

Array or infield cables (33kV) are used to connect the WTG with the substation. In all near shore projects, the grid connection could be realized either directly via the 33kV infield cables or with a step up to 150kV by a transformer station, transporting the generated power with HVAC export cables, to shore. With increasing distance between the onshore grid connection point and the wind farm, high transmission losses will exclude HVAC technology and HVDC technology has to be utilized (Slengesol et al., 2010). On example for such a HVDC converter platform is BorWin Alpha, situated in the German bight and connecting the "BARD Offshore 1" Wind farm, linking the 200km to the onshore grid connection point in Diele (Niedersachsen, Germany).

From an O&M perspective, these components are extremely important due to several reasons. Infield and export cables are the "lifeline" of the wind farm; not only securing that generated energy can be exported, but also are essential for communication, control and sustainment energy supply of the WTG. Therefore, surveys to validate burial depth and detect cable exposure have to be performed to quickly take corrective measures if needed. Cable failure due to anchor or fishing strikes would be catastrophic for the project.

The same applies to other subsystems such as switchgear, transformers, generators and the HVDC technology. Future wind farm platforms also will have to accommodate living quarters and offshore storage facilities. A good understanding of the O&M needs is therefore already relevant in the design stage of these wind power plant.

In Figure 2-2 a general overview of all the production facilities combined in one offshore wind farm is displayed to provide an illustration of the above-mentioned information.

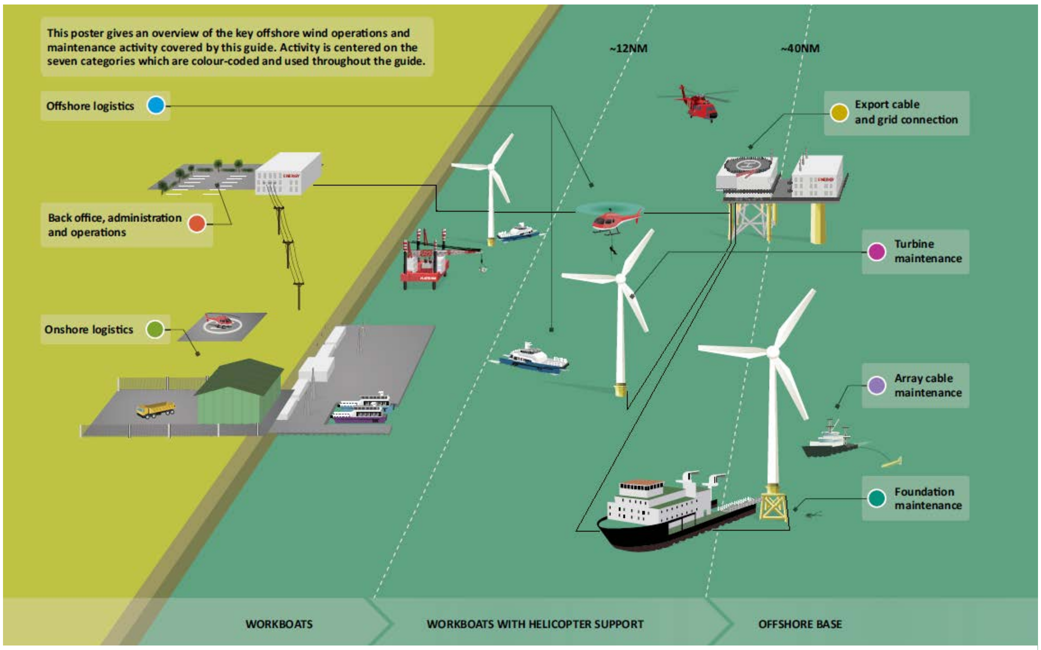

Figure 2-2: Generic overview of an offshore wind farm (GL Garrad Hassan, 2013)

2.2 Floating Offshore Wind Energy Concepts

Floating technology for offshore wind is evolving rapidly and the transition to floating offshore wind technology is essential. Bottom fixed substructures are economically feasible in water depth ~ 30-50 m (D. Roddier, C. Cermelli, & A. Weinstein, 2009). In water depth beyond 50 m the cost of fixed structures, surmount the cost for floating substructures. Many floating designs are based on proven technology from the offshore O&G sector (Böttcher, 2013, p.317). Despite the increase in complexity and many technological challenges that still need to be overcome, floating substructures also offer significant advantages (D. Roddier et al., 2009):

- Not as site dependent as fixed foundations, hence access to better wind resources in the open ocean and deep water locations;
- less sophisticated vessel are required during the construction phase, reducing installation cost; lower decommissioning cost, resulting in improved bankability. "*This is particular relevant in the context of renewable energy where capital cost and therefore access to capital is a key barrier to accelerating deployment*" (Australian Renewable Energy Agency, 2014);
- smaller environmental impact since piling operations can be avoided;
- Fewer design variations within a single project resulting in a more standardized manufacturing process.

At this time, various floating wind turbine substructure concepts are under development. The four (4) main concepts that originated from the O&G industry are: Barge-type, tension leg platform (TLP), Spar buoy type and semi-submersibles (See Figure 2-3).

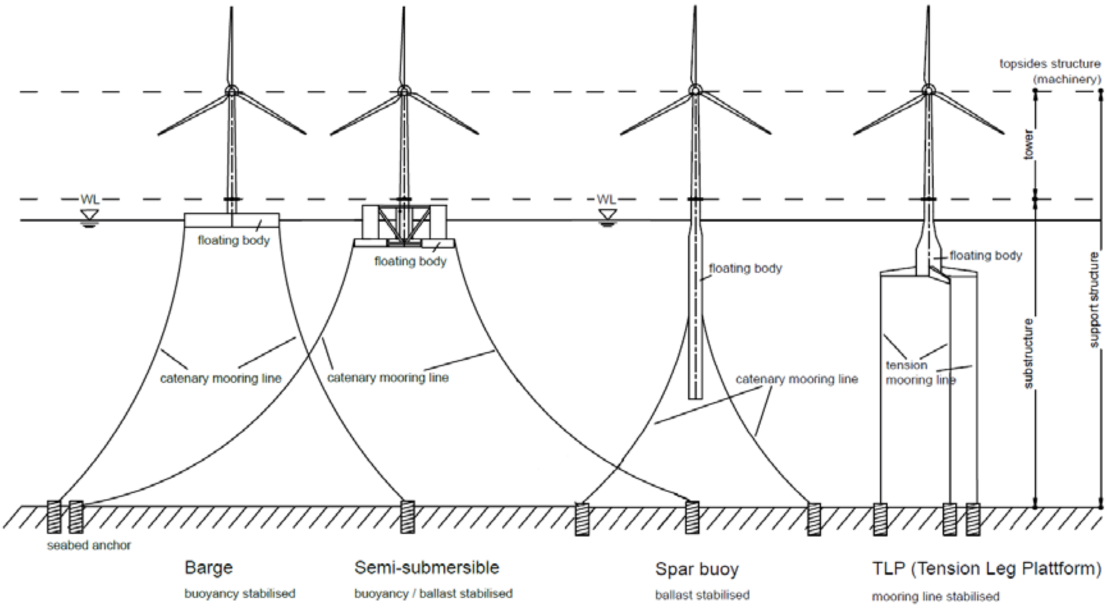

Figure 2-3: Sketches of floating offshore wind turbines with their stability principles, source: GL (2012)

The tension leg platform is a free floating but tension restrained structure. Free-floating bodies have six (6) degrees of freedom. The three (3) translational movements like heave, surge, sway and the three (3) rotational motions in pitch, roll and yaw. To reduce extreme loads acting on the turbine especially heave, roll and pitch motions should be avoided or reduced. The TLP structures achieve the best performance results and low response in motions especially in respect to heave, pitch and roll. These motions are more or less eliminated through the taut tension leg mooring system. For deep draft floaters like the spar or the semi-submersibles, heave pitch and roll motions are minimized but not eliminated (Odland, 2013). The classic spar concept is a weight-buoyancy stabilized substructure. It has a relatively large draft which can make installation and deployment difficult in some areas (Slätte & Ebbesen, 2012). From a generic point of view, heave motions less affect the spar concept. Due to the low center of buoyance and slender structure, it is less influenced by vertical wave –exciting forces.

This on the other hand causes more pitch and roll motions if compared to a semi-submersible. The semi-submersible is a free surface stabilized structure with relatively shallow draft. The larger water plane area of the semi-submersible contributes to better stability performance in pitch and roll motions compared to the spar type structure (Slätte & Ebbesen, 2012) (Roddier, Cermelli, Aubault, & Weinstein, 2010).

The TLP concept enables low structural weight, and thus lower material cost compared to the spar and semisubmersible. However, it comes with requirements to soil conditions and a costly and complex mooring system requiring sophisticated installation activities. The deep draft of the spar also results in constrains related to site selection and transport and installation (T&I) activities. The semi-submersible is the most versatile structure due the low draft and the flexibility to site and soil conditions. The culprit of this substructure is that it requires high steel mass and more complex manufacturing processes.

According to a study from DNV conducted in 2012 for the Crown Estate the spar and semi-submersible have reached the highest technology readiness level (TRL)[2] out of the four (4) categories (Slätte & Ebbesen, 2012). The WindFloat and Hywind have reached the highest TRL for floating offshore wind substructures so far. Operational since 2009, the Hywind has the most operational time of any large scale prototypes. Both, Statoil and Principle Power Incorporated (PPI), recently (end of 2015) announced that they plan to build a pilot project each with five (5) FWTU per wind farm. No TLP demo project has been deployed yet.

This report will focus only on the semi-submersible structures, specifically the WindFloat. The aim is to evaluate if a floating substructure offer the possibility to return the FWTU to shore for maintenance activates. In order to develop clear results, the most suitable concept was selected. Even with the highest TRL of all concepts the spar concept is limited because of the deep draft, and does therefore not fully supports the ‘return to shore’ service approach. Deep water but sheltered locations like Norwegian fjords would be required to return the FWTU to shore. The shallow draft of the WindFloat also allows that the FWTU is constructed and assembled in most dry-dock locations. Such assembly infrastructure could then also be used during the ‘onshore’ maintenance campaigns. Therefore, the Semi-submersible was selected as the most favorable concept to support the ‘onshore’ service approach. From a generic point of view, the semi-submersible offers the most versatile design in respect to water depth and soil conditions, paired with the low draft advantage.

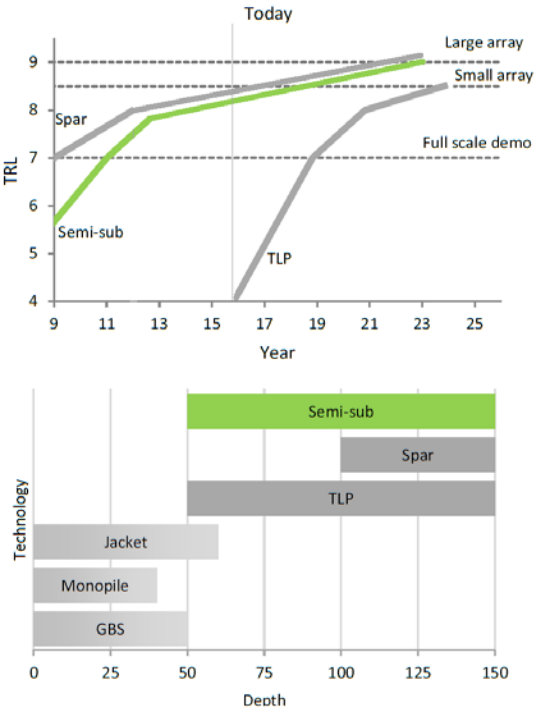

Figure 2-4: Floating structure TRL comparison, modified (Source: DNV)

> When comparing different types of offshore wind turbine structures, wave and wind induced motions are not the only elements of performance to consider. Economics play a significant role. It is therefore important to carefully study the fabrication, installation, commissioning/decommissioning costs and ease of access for maintenance methodologies. Semi-submersible concepts with a shallow draft and good stability in operational and transit conditions are significantly cheaper to tow out, install and commission/decommission than spars, due to their draft, and TLPs, due to their low stability before tendon connection.
>
> (Roddier & Cermelli, 2014, p.1)

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[2] Technology readiness level. A method of assessing technology maturity ARENA Emerging Renewables Program use of TRL framework http://arena.gov.au/files/2013/08/ERP-Tech-Readiness-Level.pdf

In addition to the technical criteria, one (1) other reasons supported the decision to select the WindFloat. The inventors of the WindFloat approached the development of the platform in rigorous scientific way. Many papers and publications are openly accessible. It therefore is best documented and in many cases only available information, particularly if compared to the other floating structure developments. This cannot be taken for granted. It is in the nature of things to be restrictive with sharing information during the design process of innovative technology. For the other projects, hardly any information is available. The publications from PPI where an important source of information and strongly contributed to this report.

2.2.1 WindFloat: Structural Layout

The following chapter section provides a detailed overview of the WindFloat, related design principles and the key components are explained, which is important in the overall content of this report.

> The challenges associated with design and operations of floating wind turbines are significant. A floater supporting a large payload (wind turbine and tower) with large aerodynamic loads high above the water surface challenges basic naval architecture principles due to the raised center of gravity and large overturning moment. The static and dynamic stability criteria are difficult to achieve especially in the context of offshore wind energy production where economics requires the hull weight to be minimal.
>
> (Roddier et al., 2010, p.2)

The WindFloat substructure is a Semi-submersible floating foundation concept (Dominique Roddier, Christian Cermelli, & Alla Weinstein, 2009 , p.1). It incorporates three (3) cylindrical shaped stabilising columns (Figure 2-5, items 2 and 3) in an equilateral triangular alignment. The three (3) columns are interconnected by horizontal and vertical bracing beams forming a truss structure (Figure 2-5, items 4 and 5). Each column is equipped with horizontal water-entrapment plates at the lower section of the column (Figure 2-5, item 6). The water entrapment plates increase the added-mass in heave and added-moment of inertia in roll and pitch, resulting in a beneficial reduction of global platform motion. In addition, the stabilising columns include internal volumes to house a static ballast reservoir and a hull trim system reservoir (Roddier & Cermelli, 2014). The hull trim system utilises pumps to move water between the columns to compensate for vertical misalignment of the FWTU caused by the wind force (thrust), hence optimising energy production. The hull trim system is a closed loop ballast system with no connection to the surrounding sea. The FWTU is kept in position by an asymmetric mooring system (Figure 2-5, item 9) (Dominique Roddier et al., 2009 , p.3).

The WTG is installed on one (1) of the three (3) columns (Figure 2-5, item 1). The turbine tower is centre positioned on the stabilizing columns. The diameter of the tower base should be close to the column diameter to allow the best possible continuity of the structure. This will help to reduce stress concentration at the tower base where large bending moment act due to overturning moments (D. Roddier et al., 2009).

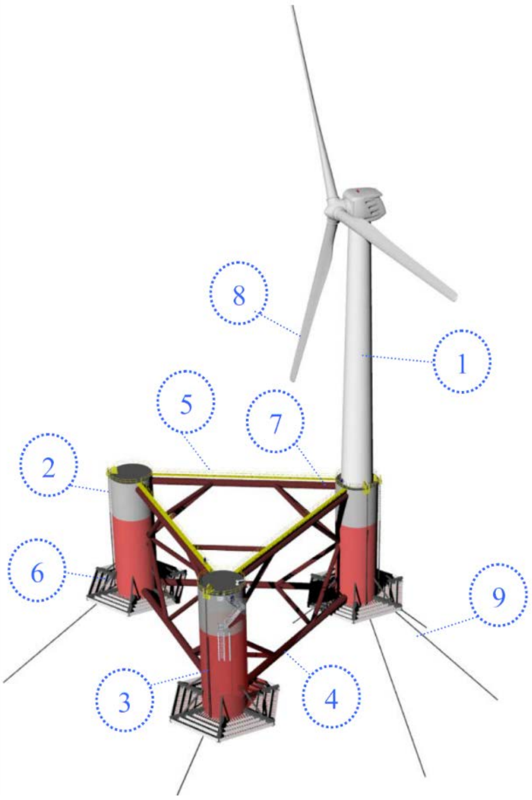


Figure 2-5: WindFloat hull and Turbine (Source: Principle Power Inc.)

Table 2-1: WindFloat main dimensions (Roddier et al., 2010)

WindFloat hull dimensions				
Column diameter	35	ft	10.7	m
Length of heave plate edge	45	ft	13.7	m
Column centre to centre	185	ft	56.4	m
Pontoon diameter	6	ft	1.8	m
Operating draft	75	ft	22.9	m
Air gap	35	ft	10.7	m
Bracing diameter	4	ft	10.7	m
Displacement	7833	st	7105	ton

2.2.2 Water entrapment plates

A key component for achieving good motion response performance for the WindFloat are the horizontal water entrapment plates fitted at the bottom of each column. Without these entrapment plates, the natural period (12 seconds) of the WindFloat would coincide with a wave frequency band with a substantial amount of energy during big storms. This would lead to unacceptable platform motions and consequently structural damage (Roddier & Cermelli, 2014).

To achieve suitable motion response values and being able to operate in waves with longer periods, a semi-submersible should be designed to achieve a larger Eigen period (i.e. Natural period) in heave T_{heave}. The natural period in heave is obtained as follows (Gudmestad, 2014):

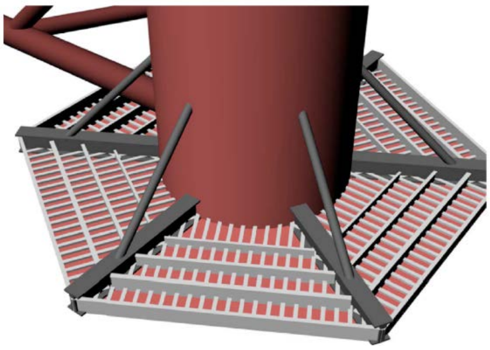


Figure 2-6 : Detail of water-entrapment plate on WindFloat (Source: Principle Power Inc.)

$$T_{heave} = 2\pi \sqrt{\frac{m_{FWTU} + m_{add}}{\rho * g * A_{waterline}}}$$

Where:

m = Mass of FWTU
m_{add} = Added mass
A = Area of column at waterline
ρ = Density of seawater
g = Standard gravity

One way to obtain a higher natural period is to increase the mass of the semi-submersible. Increasing the size would consequently lead to higher material cost, hence not a favorable option. A simple solution to this problem is to increase the amount of motion-displaced water, which will increase the added mass. *"The added mass can be increased by mounting spoilers to the barge ('bilge keels')"* (Gudmestad, 2014), see Figure 2-7.

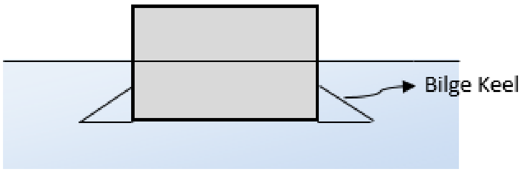


Figure 2-7: Barge with increased added mass, source: (Gudmestad, 2014)

The heave plates on the WindFloat serve the same purpose like bilge keels. The plates increase the hydrodynamic inertia and added mass in heave due to the greater amount of motion-displaced water. Additional damping forces are generated due to the vortices that occur at the edge of the entrapment plates. With entrapment plates the natural period of the WindFloat can be increased to 20 seconds (Kvittem, 2014; Roddier & Cermelli, 2014). Especially for a relatively small structure like the WindFloat and with high demands for cost competitiveness, the water entrapment plates are effective solution to achieve the required natural period in heave.

2.2.3 Ballast systems

The WindFloat structure can have two (2) ballast systems. The static ballast system and an active ballast system. The static ballast reservoir is situated in the bottom of each column (see Figure 2-8). If emptied the WindFloat draft is reduced, which is beneficial during tow-out operations and shallow water transport. Once the installation site is reached, the permanent water ballast is pumped into the static reservoir to lower the WindFloat to its operational draft (Roddier et al., 2010 , p.6). Lowering the center of gravity for the operational mode improves the overall stability performance and reduces the motion response of the WindFloat. The closed loop active ballast system or hull trim system on the other hand is not used to compensate for dynamic motions of the floater. The wind force acting on the FWTU will induce an overturning moment on the support structure. This may result in a slight loss of optimal vertical alignment. To achieve ideal energy production, the WTG tower must remain vertical. Therefore, water is pumped between the columns to keep the platform in a vertical up-right position. The hull trim system is a closed looped system completely isolating the water in the trim system from the surrounding sweater. This is to prevent possible flooding and loss of stability of the FWTU (Roddier & Cermelli, 2014).

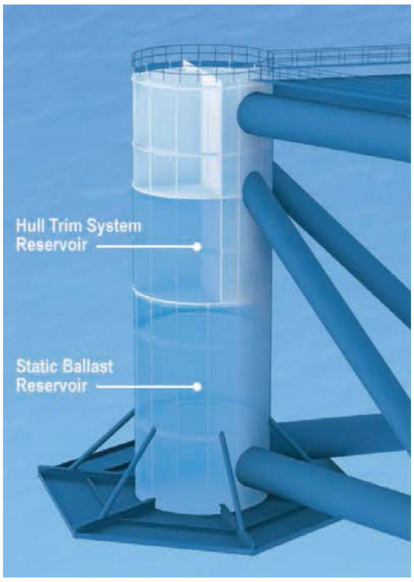


Figure 2-8: Static ballast and hull trim system (Source: Principle Power Inc.)

2.2.4 Mooring and anchors

Station keeping for semi-submersible structures is achieved with the help of mooring lines anchored to the seabed. These can be taut or catenary. Catenary mooring systems are generally used for shallow to deep-water applications. The water depth for most close to shore but deep-water locations suitable for offshore wind energy projects will allow for catenary mooring systems to be the system of choice. The weight of the catenary system is unlikely to become a limiting factor like for ultra-deep-water locations. This report will therefore only consider the use of catenary mooring systems.

The catenary mooring system makes use of the suspended line weight and the resulting forces in the mooring lines to keep the floating structure in place. The catenary therefore can be described as the resulting shape of a free hanging line under gravitational influence (Gudmestad, 2014).

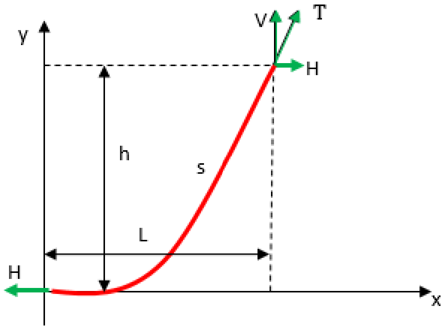


Figure 2-9: The hanging chain, the catenary, source: (Gudmestad, 2014)

The formula used to mathematical describe the geometry of a catenary mooring line is (Gudmestad, 2014):

$$y = \frac{W}{H}\left(\cos\frac{W}{H}\,x - 1\right)$$

Where:

T = *tension in mooring line*
V = *vertical component of the tension*
H = *horizontal component of the tension*
s = *length of chain on the sea floor*
L = *horizontal length from the point where the tension is applied to the seafloor*
h = *water depth*
W = *submerged weight/m of the hanging chain*

From this relation it is possible to obtain the formulas to compute the length of catenary; Water depth; Horizontal force; Distance to anchor; Vertical force and the Tension for the mooring layout. In general, a catenary mooring system comprises the following major components:

Table 2-2: Major mooring components (Smith, Brown, & Thomson, 2015)

Main Category	Description
Foundation	Embedded Anchors, Driven Pile, Suction Pile, Gravity base and Lower Tendon Connector
Connectors	Long Term Mooring Shackle, Links, Subsea Swivel, Subsea Mooring Connector (i.e. Ballgrab), Open Socket and Upper Tendon Connector
Mooring Lines	Polymer rope, coated Wire rope, Chain and Tubulars (Tendons)
Tensioning & Hang Off	Fairlead Sheave, Guide Tube, Chain Tensioner, Tendon Connectors and Chain Lockers

The foundations of the mooring system are chosen based on the soil conditions. Commonly used foundations types are either drag embedded anchors or suction piles. The anchors and piles are dimensioned to withstand the horizontal force H from the mooring lines. Vertical loads (pull out) caused by dynamic motions could pull the anchor out of the soil and lead to anchor failure. To reduce the possibility of vertical loads acting on the anchor additional length of mooring line is installed between the touch down point and anchor (Gudmestad, 2014). This part of the mooring line is often a chain section. Connected to this chain section is a coated wire rope or polymer rope. If a chain-tensioning device is used to set the mooring tension, the upper section of the mooring line will be a chain again. Such a mooring line set up, utilizing conventional polyester ropes, chain and drag embedded anchors, was installed on the WindFloat demo project in Portugal (Smith et al., 2015).

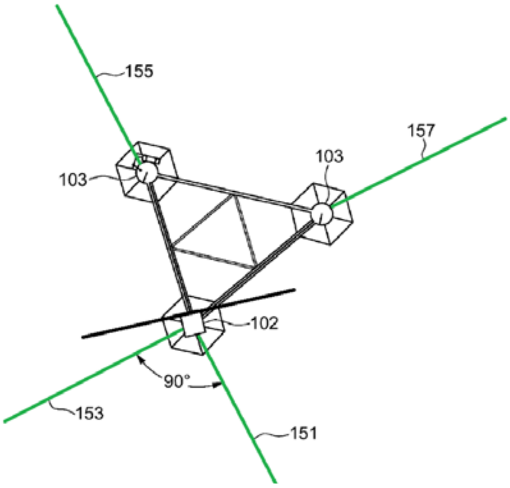
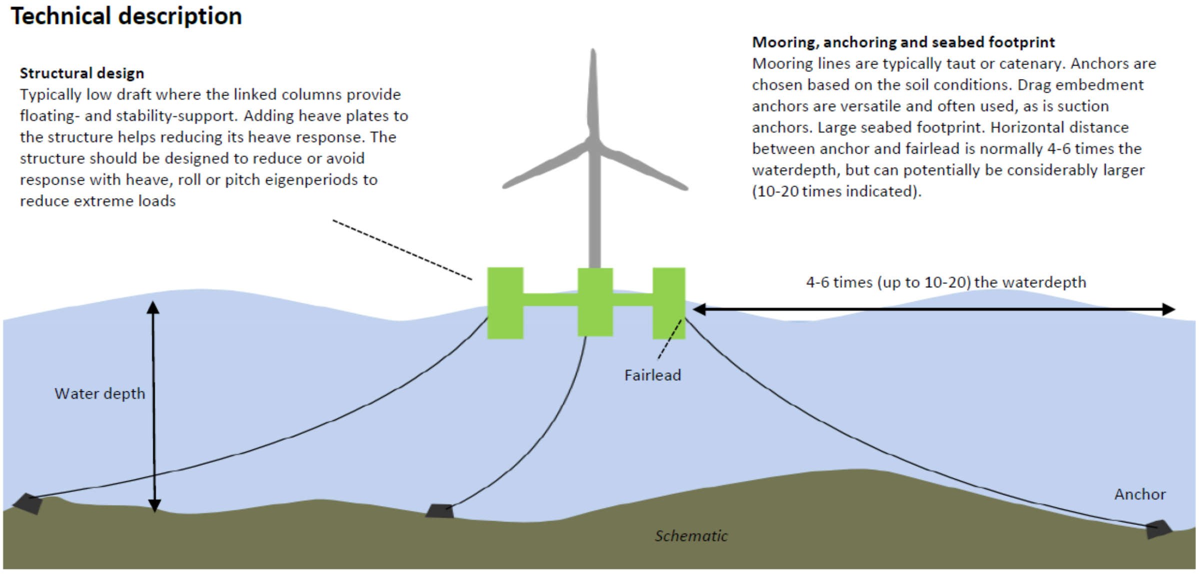


Figure 2-10: Top view of the WindFloat with asymmetric mooring system (Source: Principle Power Inc.)

The mooring plan of the WindFloat foresees a four (4) line or a (6) line mooring set up. Figure 2-10 displays the top view of the WindFloat with a four (4) line set up. In the four (4) line design the mooring lines (green) are arranged in an asymmetric manner. Two (2) lines (item 153 &151) are coupled to the column supporting the wind turbine (item 102) and one (1) line is connected to each of the remaining columns (item 155 &103) (item 157 & 103). The two (2) lines connected to the tower support column are spread by an approximately 90-degrees angle. (Roddier & Cermelli, 2014). The proposed mooring line set up foresees a chain section with clump weights at the top and polymer rope for the intermediate section. In the bottom segment a chain section is connected to a drag-embedded anchor (C. Cermelli, Aubault, Roddier, & McCoy, 2010). Anchors and mooring lines are installed prior to the transport and installation (T&I) of the FWTU.

This is referred to as a two (2)-phase installation campaign. First, the foundations (anchors) and parts of the substructure (mooring lines) are set. After laying the drag anchors, they are teste to the maximum design force. Once the lines and anchors have been tested, an abandonment and recovery (A&R) system is installed to support the pick and hook-up operation (Smith et al., 2015). Further information on the installation process and anchor-handling vessel (AHV) capacity can be found in (Smith et al., 2015).


Technical description

Structural design
Typically low draft where the linked columns provide floating- and stability-support. Adding heave plates to the structure helps reducing its heave response. The structure should be designed to reduce or avoid response with heave, roll or pitch eigenperiods to reduce extreme loads

Mooring, anchoring and seabed footprint
Mooring lines are typically taut or catenary. Anchors are chosen based on the soil conditions. Drag embedment anchors are versatile and often used, as is suction anchors. Large seabed footprint. Horizontal distance between anchor and fairlead is normally 4-6 times the waterdepth, but can potentially be considerably larger (10-20 times indicated).

Figure 2-11: Mooring, anchoring and seabed footprint schematic (Slätte & Ebbesen, 2012)

During the initial design phase of the WindFloat no standards specific to floating offshore turbines existed. For the design basis (mooring lines) of the WindFloat, the safety factors from API RP 2SK, Recommended Practice for Design and Analysis for Station keeping Systems for Floating Structures (The American Petroleum Institute, 2005) were applied. Hence, standards from the O&G industry as well as onshore wind sector had to be used (Roddier et al., 2010). The existing offshore wind standards for bottom fixed wind turbines did lack floater specific issues, e.g. stability, station keeping and so on. For an emerging and cost intensive technology it is however crucial and necessary to have design standards. This will help the industry to develop further and contribute to rise the CRI. In 2011, DNV launched a joint industry project (JIP) to develop a full-fledged DNV standard for the design of floating wind turbine structures. The Standard DNV-OS-J103 Design of Floating Wind Turbine Structures (DNV, 2013) is a supplement to the DNV-OS-J101 (DNV, 2007) and was published in June 2013. The focus is on floater specific design issues and the following technical topic are covered in the standard (Hopstad, Ronold, & Slätte):

- Safety philosophy and design principles
- Site conditions, loads and response
- Materials and corrosion protection
- Structural design
- Design of anchor foundations
- Stability
- Station keeping
- Control and protection system
- Mechanical system and electrical system
- Transport and installation
- In-service inspection, maintenance and monitoring
- Cable design
- Guidance for coupled analysis

Apart from the flexibility regarding site selection and water depth, the floating substructures offer a major additional advantage. No costly and sophisticated Jack-Up units are required during installation. Most T&I activities can be performed by standard seagoing tugs, anchor handling tug supply (AHTS) vessels or offshore support vessel (OSV) which are significantly cheaper and have better weather restrictions then the Jack-Up units. This further allows to use a two (2) phase installation campaign. Meaning all the installation activities for the foundations (Anchors) and parts of the substructure (mooring lines) as well as the sea cables can be installed prior to the FWTU. Multiple units can be used, each optimized to achieve the lowest possible weather restrictions. This reduces the possibility that one (1) unit has to wait for the other, due to different weather restrictions or delays. This strongly supports the by nature series installation process for offshore wind farms. That improves the plannability of installation campaigns and lowers the risk from break downs or unforeseen events.

2.2.5 Secondary Steel

Secondary steel is the term used for all the equipment such as boat landing, platforms, ladders and helipads. The boat landing (BL) is used to access and exit the wind turbine. It consists of two (2) parallel pipe like steel fenders enclosing a ladder. It is mostly clamped, welded or bolted to the primary steel structure of the foundation. During the embarking process a small vessel, often referred to as crew transfer vessels (CTV), pushes against the two (2) metal fenders, to stay in position, allowing the crew members to step over and access or exit the structure. Boat landings are the most common way to access offshore wind turbines. Some designs offer multiple boat landings on one (1) substructure. This improves accessibility since the CTV's can choose the optimal angel of approach to the prevailing wave and swell direction.

The WindFloat has a boat landing installed one (1) or two (2) of the columns to provide access CTV. The individual columns are interconnected with main beams and bracings. The top main beams also allows personnel to get from one (1) column to the other via a mounted gangway. The height of the upper deck will be designed to provide sufficient air gap such that the highest expected wave crest cannot damage the turbine blades or deck equipment (Roddier et al., 2010 , p.8). Other deck equipment or secondary steel equipment will depend on project specific requirements to support the chosen O&M concept, e.g. Heli winch down point.

2.3 Wind Turbine Generator

Wind energy is the kinetic energy of the volume movements of air in the earth atmosphere. It is an indirect form of solar energy and therefore considered as a renewable power source. The use of wind energy through sails and windmills as a power source dates back to ancient history. A wind turbine generator first converts the kinetic energy from the wind into a rotary motion which is then converted to electricity (Hau, 2014). The general used turbine type is a three bladed design. One of the design criteria from PPI for the WindFloat to achieve performance levels that would allow the use of existing and customary in the market available turbines with as little requalification as possible. In this report, we assume the use of common 5 MW offshore turbine that in most cases are solely designed for offshore deployment and have been increasingly implemented in resent offshore wind projects. No specific 5 MW turbine was chosen.

2.4 Operation and Maintenance

Having outlined the floating foundation technology, this section will provide an insight to the current state of the art for operating and maintaining an offshore wind power plant. Current strategies and the industry standard will be presented in short to help understand the related challenges and limitations. Presented in addition are various influencing factors like weather restrictions and maintenance methodologies to deliver a full picture.

2.4.1 Offshore wind operation and maintenance overview

The offshore environment sets higher demands and requirements to the turbine service compared to an onshore location. Onshore wind farm availability ranges from 95% to 98% whereas for offshore locations only 80% - 95% is reached (Slengesol et al., 2010). Onshore turbines are easy to access and maintenance practices are well established. Offshore wind operations and maintenance (O&M) however is still in its beginning and a best practice has not yet emerged. Constant development takes place as experience starts to build up and more wind farms enter the operational phase (GL Garrad Hassan, 2013).

As offshore wind farms increase in size and distance to shore rises, logistics and access technology become increasingly important (GL Garrad Hassan, 2013 , p.5). Getting technical personal transferred to the turbine safely, most of the time, quickly and cost effective is a key objective of every operation and maintenance strategy. Access restrictions due to poor weather conditions is one of the prevalent contributors to high O&M cost and lost production. According to the guide on ‘UK Offshore Wind Operation and Maintenance’ by GL Garrad Hassan the cost for O&M activity’s account for approximately one quarter of the lifetime cost (Slätte & Ebbesen, 2012) and for up to 30% of the cost of energy (J. J. Nielsen & Sørensen, 2011). Cost reduction is therefore an important factor in the relatively young offshore wind industry. Partially those costs are caused by the access restrictions described in the previous chapter.

2.4.2 Offshore logistics

Trends develop towards further from shore and increasing park size with huge number of turbines as technology maturity progresses. This influences the logistic concepts. Of course, no wind farm project is comparable. Each project has different site specific characteristics which influences the chosen operation and maintenance approach (GL Garrad Hassan, 2013). The main factors are:

- Distance to shore as the most prevalent factor;
- Distance to nearest service hub or Harbour;
- Balance of plant layout;
- Average sea state;
- Park size and number of WTG

Depending on those characteristic three (3) main logistical strategies have emerged. Of course, some projects also incorporate a combination of those approaches to cater for varying project characteristics. Broad strategic approaches to offshore logistics. The three (3) most common logistical approaches supporting O&M as stated in “A Guide to UK Offshore Wind Operation and Maintenance” (GL Garrad Hassan, 2013) are displayed in Figure 2-12.

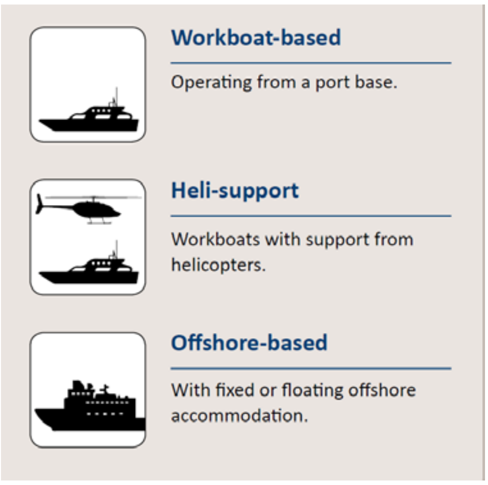


Figure 2-12: Broad strategic approaches to offshore logistics (GL Garrad Hassan, 2013)

In the **Workboat-based**, approach a crew transfer vessels (CTV) transport the maintenance technicians from the service hub to the wind farm and back. This is especially suitable for nearshore locations with a minimal distance between the service hub and the wind power plant. With increasing distance to the wind farm the traveling time increases. This reduces the net working per shift and the increase in transit time ($T_{transit}$) upturns the mean time to repair (MTTR). Hence, a short MTTR is needed in order to minimise lost production and get a high average availability values.

The **Heli Support** strategy utilises the benefits from the helicopter for fault clearance or reactive repair. This is mostly complementary to the usage of the workboats. Scheduled activities will predominantly be performed utilising CTVs to transport and transfer the technicians. When response time is critical to limit lost electricity production helicopters become more suited with increasing distance to the service hub (GL Garrad Hassan, 2013). The use of helicopters not only reduces $T_{transit}$ significantly but mostly offers a large weather window for access operations with wind speeds of up to 20m/s (Böttcher, 2013 , p.450). Correlation between Wind and wave is site-specific. Heavy rainfall and low visibility can reduce those advantages again. Helicopter transfer is more expensive (find source).

Offshore-based approaches are implemented for wind farms where the transit distances require the service hub to be located offshore. In *A Guide to UK Offshore Wind Operation and Maintenance* (GL Garrad Hassan, 2013) this 'transition point' from onshore based to offshore based is said to be (40) nautical miles (NM) from the nearest service hub. The respective $T_{transit}$ would be so large that the net remaining working time would not be economic. Figure 2-13 displays the relation between O&M cost and the distance to the nearest service hub. In the Offshore based approach, the technical personal is housed on a fixed or floating accommodation in the wind farm. The accommodation units are integrated in the converter platform. The technicians are then transferred via boat landing and CTV. Helicopters support is used in addition. Offshore support vessel (OSV) are the floating alternative. Personal access is realised via fast rescue boats (FRB), CTVs and heave compensated gangways, e.g., Ampelmann[3] or the Uptime system[4]. In some cases even a combination of fixed and floating concepts are used. The platform provides a limited number of bunks to accommodate the technicians needed for the regular service workload. For lager service campaigns OSV, i.e., 'Walk 2 Work' Vessel, Flotel ships are hired. These campaigns are preferably performed during the summer period to reduce the risk of poor weather conditions, hence access limitations, as well as lost production caused by the shut down during the maintenance operation.

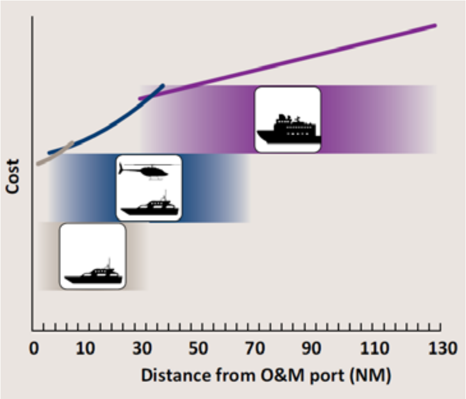


Figure 2-13: O&M strategy cost as a function of distance (GL Garrad Hassan, 2013)

The above factors illustrated the 'external' factors that influence O&M concepts. Adding to the complexity are the 'internal' factors, e.g., ownership and contracts as well as the maintenance methodologies. Described below are the most predominant ones.

2.4.3 Maintenance Types and Methodology's

Maintenance activities can be subdivided into preventive and corrective maintenance (Wiggelinkhuizen et al., 2008). In *Assessment of Condition Monitoring Techniques for Offshore Wind Farms,* maintenance types are described as follows:

> Corrective maintenance is performed after a breakdown or if an obvious fault has occurred. Preventive maintenance is intended to prevent equipment breakdown and consists of repair, service or component exchange. Preventive and corrective maintenance can be split up further. For wind turbine technology, the following subcategories seem to be appropriate. (See also Figure 2-14).
>
> (Wiggelinkhuizen et al., 2008 , p.1)

2.4.3.1 Preventive maintenance:

- Calendar based maintenance, based on fixed time intervals or on fixed numbers of operating hours.
- Condition based maintenance, based on the actual health of the system. This requires online condition monitoring systems and inspections.

2.4.3.2 Corrective maintenance:

- Planned maintenance, based on the observed degradation of a system or component (a component failure is expected in due time and should be maintained before it occurs).
- Unplanned maintenance, necessary after an unexpected failure of a system or component.

(Wiggelinkhuizen et al., 2008 , p. 1)

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[3] http://www.ampelmann.nl/

[4] http://www.uptime.no/

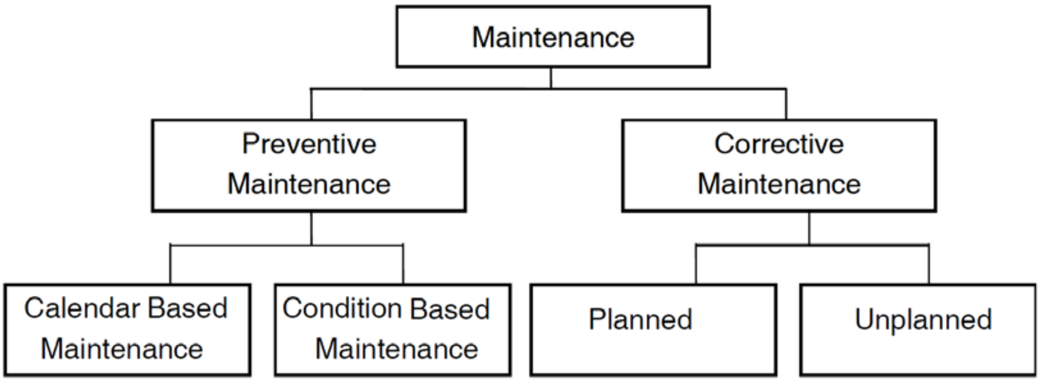

Figure 2-14: Schematic overview of different maintenance types (Wiggelinkhuizen et al., 2008)

2.4.3.3 Unscheduled Maintenance

Unscheduled maintenance refers to the maintenance activity's that have to be carried out on an ad-hoc basis when a wind turbine went into failure mode. This is the unplanned corrective maintenance displayed in Figure 2-14 (GL Garrad Hassan, 2013). The aim of every offshore wind O&M strategy should be to reduce this type of maintenance to a level as low as economically reasonable. Unscheduled maintenance causes additional expenses due to the additional downtimes caused by the preparation and reaction period (Time to organise, mobilisation time, travel time) and the associated energy production loss. Of course, unscheduled maintenance cannot be avoided completely and always will be a part of every O&M strategy.

2.4.3.4 Scheduled Maintenance

Scheduled maintenance (SM) includes all time regular service activities that are required to keep the wind turbine running. Typically, offshore wind turbines and POB are subjected to a defined scheduled maintenance program involving a major service in certain time intervals. Commonly this comprises an annual service and a three (3) or five (5) year major overhaul. This varies between the different original equipment manufacturer (OEM). Project owner strategy and certification requirements, supplemented by periodic inspections regimes can further influence the workload. The scheduled maintenance is usually undertaken during the summer month. The average metocean conditions during the summer are more favourable. This moderates lost production owing to the lower average wind speeds, also providing more favourable weather windows for turbine access (GL Hassan).

2.4.4 Access and crew transfer operation

The accessibility of the turbine has a major influence on the availability of the WTG. Metocean climate conditions are the root cause to the two (2) main factors that influence accessibility. The harsh environmental conditions cause higher wear and hence require more frequent service and reliable components. Access limitations due to poor weather is the other critical factor. Waves, swell waves and sea currents, high winds and low visibility are the primary source for access restrictions. Bad weather can therefore reduce the effective offshore working time by a factor of up to 50% per month (Slengesol et al., 2010 , p.65). However, each project differs significantly and accessibility and logistic concepts have to be adjusted individually.

An important part of every O&M strategy is therefore to assure the safe and efficient personal transfer with the lowest possible weather restrictions. Boat landing are the preferred choice in most projects, especially for near shore projects. Accessibility limits then depend on the wave height, typically at maximum significant wave height H_{m0} of 1.5 m (Slengesol et al., 2010). Offshore support vessel (OSV) equipped with motion compensated gangways, e.g. Amplemann or Up-Time are increasingly used for projects further from the coast. These concepts achieved good results and personnel transfer is possible to a significant wave height H_{m0} of 2.5 m. This is also referred to as 'Walk to Work' (W2W), hence the vessels are denoted as W2W vessels.

Complementary to the marine operations, access by aviation operations can be used to support the offshore wind farm activities. Most turbines are equipped with a Heli hoist maintenance platform and service technicians and material is Heli lifted and winched down to the turbine. In North Sea areas, weather conditions can remain bad for a long period especially during the winter month. Prohibiting access by marine vessel operations this can lead to a significant loss of production in a short time (Drwiega, 2013). Helicopters hoist operations therefore increase the accessibility. Hoist access operations however are restricted by wind speeds greater than 20 m/s (Böttcher, 2013) and are also hindered when the visibility falls below 3 km. Access by aviation is therefore complimentary to marine support for offshore wind farms, each being relevant depending on the task and as weather conditions and maintenance type dictate (Drwiega, 2013).

Chapter 3

3 Idea and Methodology

3.1 On-site vs. on-shore maintenance

In the above chapters, the major parameters and conditions, which influence O&M concepts, are described. This overview outlines the complexity involved when developing an O&M strategy. It should also make clear that in most cases, the concepts have to be adapted to cater for site-specific criteria and there cannot be a 'one fits all' solution. It adds to the overall complexity since every concept has to be tailored to some extent. However, most fundamental principles will remain the same for each project.

'On-site' or 'in-situ' maintenance refers to all the maintenance work that is executed offshore in the wind farm. The technicians and equipment have to be transported from the services hub, platform or OSV to the wind farm and turbine. Taking all the above into consideration it concludes that 'on-site' maintenance activities for maritime energy plants, are strongly influenced by metocean conditions, affecting numerous logistical operations, hence are complex and hard to plan, all contributing to high O&M costs.

Since the shallow draft floating wind technology offers the opportunity to return the turbine to shore, the logical consequence is to execute the service in this more favourable environment. Among others, this has been proposed by Alpha Wind (LLC, January 2015). It would largely eliminate the access limitations caused by poor weather conditions. Once returned to shore the maintenance could then be carried out in a dry-dock or service harbour, without access limitations and around the clock. This is referred to as the 'onshore' maintenance approach. The idea behind the onshore service approach is to be able to conduct the maintenance task in a quicker, safer and more efficient way. Removing access restriction by relocation the turbine back to a more manageable environment. This will eliminate many of the limitations the 'on site' maintenance approach faces and offers the option to carry out high quality maintenance. This has many advantages: Work will be more effective, inspections can be carried out much quicker and for a fraction of the cost and with generally lower HSE risk. Accessibility will not be a problem since the FWTU is secured to the kay-side, dry-dock or in a sheltered bay. Available working time will not be reduced by the travel time, weather restrictions and daylight. Logistical complexity and cost can be reduced to a minimum.

However, there are also a few limitations, which have to be taken into account, as they are not straightforward. Detaching and returning a FWTU to shore is a highly complex task and requires good procedures and careful planning since multiple vessels and teams are involved. It also sets high requirements to the mooring and cable connection of the FWTU. During the time the turbine is disconnected it is not able to produce electricity, which will contribute to the overall downtime. The duration of the transport and installation (T&I) procedures therefore have to be accounted for in addition to the time required to do the maintenance. Depending on the complexity of the T&I procedures this can quickly be a time intensive process and therefore eliminate all the advantages gained from an 'onshore' campaign.

The question therefore is whether the 'onshore' service approach can be an economical and technical feasible alternative to the 'on-site' maintenance. This can be studied by computing the cost for each strategy and do a comparison. The results aim to help develop a detailed understanding of the opportunity's and limitations the semi-submersible substructure technology offers in respect to operating and maintaining a floating wind farms.

3.2 O&M cost computation methodology

This chapter section describes the approach chosen to compute comparative values that would allow a distinction between a regular 'on-site' maintenance strategy and one where the turbine is returned to shore.The goal is to compare the cost for the 'on-site' offshore maintenance with a realistic and suitable onshore service strategy. This must be done in a structured approach in order not to compare two (2) different things. A straight line of investigation has to be followed to get comparable results. First, a workload was specified that is suitable for an onshore service approach. Returning a FWTU for just a minor reactive repair can logically be ruled out in general. The focus has to be on the larger and scheduled maintenance tasks. After defining what kind of maintenance work is suitable for the 'onshore' service operation the net-working time to do this workload has to be calculated. When the amount of net-working time is known, the aim should be to compute the cost resulting from either conduction the work 'on –site' or 'onshore'. The cost of each strategy then reveal economic feasibility. This price tag for each strategy consist of three (3) main cost blocks: Vessel cost, labor cost and lost production.

A selected approach chosen is as follows:

1. Define the general guidelines and principles that have to be followed for both strategies.
2. Define the workload that is suitable for an onshore service campaign.
3. Develop a detailed work breakdown structure (WBS) for the T&I process.
4. Identify the most sensitive operation and determine the limiting weather restriction.
5. Use the method statements to compute the planned operation period or net-working times needed.
6. Develop all other input data like, weather restrictions, vessel and labor cost, energy production.
7. Add the statistical weather downtime for different month to compute the total estimated duration to complete the maintenance workload.
8. Assign resources needed and caused lost production to complete workload in the offshore or onshore scenario.
9. Compare the cost from the 'onshore' campaign to the 'offshore' approach.

Defining the maintenance workload that is suitable for an onshore service strategy and should serve as a benchmark measure was the first step. To complete this workload package applying the different strategies will then result in a price tag for every O&M strategy. Of course, the applied maintenance methodology will have an impact and cannot be neglected. Corrective maintenance is the simplest strategy, but the failure of a minor component can easily escalate, resulting in a more severe damage or major component failure. This causes significant repair cost and downtime, hence additional cost due to lost energy production. Consequently, the cost for corrective maintenance are linked with much larger uncertainty then preventive maintenance (J. J. Nielsen & Sørensen, 2011). In addition, only the preventive methodology seems to be a meaningful match to the 'onshore' strategy. Thus, a preventive maintenance methodology in combination with the 'on-site' and 'onshore' strategy is assumed in this paper.

In a comparative study on O&M concepts, it is very important to consider the lost energy production caused by the maintenance work. If the onshore strategy requires rather expensive vessels, it still can be more economically if the duration of the maintenance period is significantly shorter and lost energy production is kept minimal. Therefore, this cannot be passed over in the calculation.

It is also of great interest to find out how the distance to shore will influence the results. As we know from the previous chapters, with increasing distance to shore other strategies had to be applied to do be able to deliver cost effective maintenance. This will be somehow similar for floating wind power plants. Therefore, in addition to the 'onshore' and 'on-site' scenarios, three (3) cases will be defined with varying distances to shore.

MS-Excel was used to perform all computations. It offers the best platform to quick and easily process various different types of data. In addition, most data can be easily interconnected. Other tool like MS-Project require relatively specific input data. MS-Excel offered the best flexibility in this respect.

The central principles mentioned earlier was that it was necessary to outline some sort of guideline that could be followed throughout the analysis. Since data was not always fully available and a very novel technology was looked at, multiple assumptions had to be made. Following those guidelines helped to structure the analysis.

- The principal for each O&M strategy is to conduct as much work as possible during the summer season, to minimize shut downs and lost production during the high wind season in the winter month.
- The aim should also be to cope with the workload with existing resources and see how fare on could get before taking in an additional vessel /or units by extending the project duration towards the winter season. The baseline resources defined, should be comparable to industry standard for a comparable project size.
- In the case of missing data, one should look at similar applications and solutions, or use best engineering judgment to develop estimates.
- A conservative approach to towards safety factors, weather restrictions and duration for selecting and assigning parameters. However, the values should be as close to practical values as possible, in order to obtain robust but comparable results.
- Only the current state of the technology is looked at. The parameters used in the computations should reflect existing or proven technology.

The above guiding principle where used to establish the values, parameters and set-up used in the analysis. In addition, it also let to the conclusion that it only would be reasonable to do this comparison for a large-scale project in order to be able to put the results into perspective. That is why a 400-MW offshore wind farm was selected, despite making it far more complex, instead of just a single FWTU. To have a reference the ‘on-shore’ set up could be compared to, the offshore or ‘on-site’ maintenance scenario was applied to the matching wind farm case (similar distance). The ‘on-site’ scenario computation for every case therefore serves as the baseline that the ‘onshore’ scenario is compared to. The price tag for the respective O&M strategy in both scenarios always cover three (3) cost components (Labor cost, vessel cost and lost production). Since exactly the same workload serves as the base in every computation, the spare part and material cost are regarded as constants and henceforth excluded from the analysis. Only a five (5) year period will be studied.

3.2.1 Comparative metric

Two (2) common approaches used as a comparative metric to evaluate strategic decisions for offshore projects are the cost of energy (COE) or levelized production cost (LPC) method. The COE computation method is an analysis of costs and energy production, covering all life-cycle phases of an offshore power production facility. In the NREL report from 2013 the following equation was utilized (Maples, Saur, Hand, van de Pietermen, & Obdam, 2013):

$$LCOE = \left(\frac{ICC * FCR}{AEP}\right) + O\&M$$

Where:

$ICC = OCC + (OCC * CF) = Installed\ Capital\ Cost$
$OCC = TCC + BOS + Soft\ Costs = Overnight\ Capital\ Cost$
$FCR = Fixed\ Charge\ Rate$
$O\&M = Operation\ and\ Maintenance$
$AEP = Annual\ Energy\ Production$
$TCC = Turbine\ Capital\ Cost$
$BOS = Balance\ of\ Station\ Cost$
$Soft\ Cost = Insurance + Contingency + Decommissioning$
$Insurance = (TCC + BOS) * 0.02$
$Contingency = (TCC + BOS) * 0.1$
$CF = Construction\ Financing$

The LCOE method however was considered not suitable to deliver clear results. Many of the values included in the calculation, e.g., ICC, TCC, BOS, etc., would have to be considered as constants. Both approaches focus on a high level analysis of the whole park and spanning over the expected lifetime. In order to be able to distinguish between two (2) different O&M strategies, mainly the O&M have to be studied.

Furthermore, it was difficult to collect precise information to generate these constant values for a floating wind farms. Accurate investment cost are still difficult to estimate as the projects are only in the prototype phase and therefore not representative (Slätte & Ebbesen, 2012). Data from project owners and companies are not available. Thus, the same holds for the LPC method. This concluded that only the O&M cost itself are calculated and used as the comparative value in order to distinguish between the 'on-site' and 'on-shore' maintenance approach. Other commonly used methods like the described above would only add complexity without any significant contribution in accuracy and quality of data.

3.2.2 General approach

Due to the high costs associated with offshore wind maintenance activities, there is an increasing demand for simulation tools that compute O&M cost during the planning and operational phase. Many simulation models like the ECN O&M calculator[5], Shoreline's MAINTSYS™[6] and others have evolved in the last years and continued improvement and development is taking place. Researchers are targeting this field and papers and research literature is more widely available (Dinwoodie, Endrerud, Hofmann, Martin, & Sperstad, 2015). A well-structured model based approach for computing offshore operation and maintenance methodologies is presented in *On risk-based operation and maintenance of offshore wind turbine components* (J. J. Nielsen & Sørensen, 2011). Nielsen and Sørensens (2011) used the model simulation to compare condition-based maintenance against the use of a corrective maintenance approach for a generic offshore wind turbine. "*The condition-based strategy was found to give a larger number of repairs through the lifetime of the structure, but most corrective repairs could be avoided*" (J. J. Nielsen & Sørensen, 2011). This supports the principal idea of the 'onshore' maintenance approach. In the 'onshore' approach, as much service-workload as possible has to be integrated into the onshore overhaul, to make it effective and reduce all other reactive maintenance actions as far as possible. Based on these considerations the following conclusions derive:

1. Planned maintenance (condition based and scheduled maintenance) should be conducted to prevent most ad-hoc and reactive repair activities.
    - This will reduce the uncertainty in the maintenance planning and reduce the associated lost energy production.
    - A condition based strategy with inspections and preventive maintenance will reduce corrective repairs.

2. For this preventive and scheduled maintenance the turbine is returned to shore
    - This will eliminate the access limitations for the actual maintenance duration

3. It is self-evident that not all maintenance task can be carried out onshore and that the FWTU is not brought back for every repair. Corrective maintenance will be handled in-situ, even if an onshore strategy is chosen.
    - Therefore, the corrective maintenance workload is considered as a constant and intentional excluded in both strategies.

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[5] https://www.ecn.nl/extranet/omce/

[6] http://shoreline.no/

In line with this maintenance methodology, a total annual workload is computed, comprising all inspection and repair times. The total annual workload of a single FWTU consist of the unplanned corrective maintenance (e.g. responsive repair), scheduled maintenance (e.g. annual service regime) and inspections due to certification and regulatory requirements.

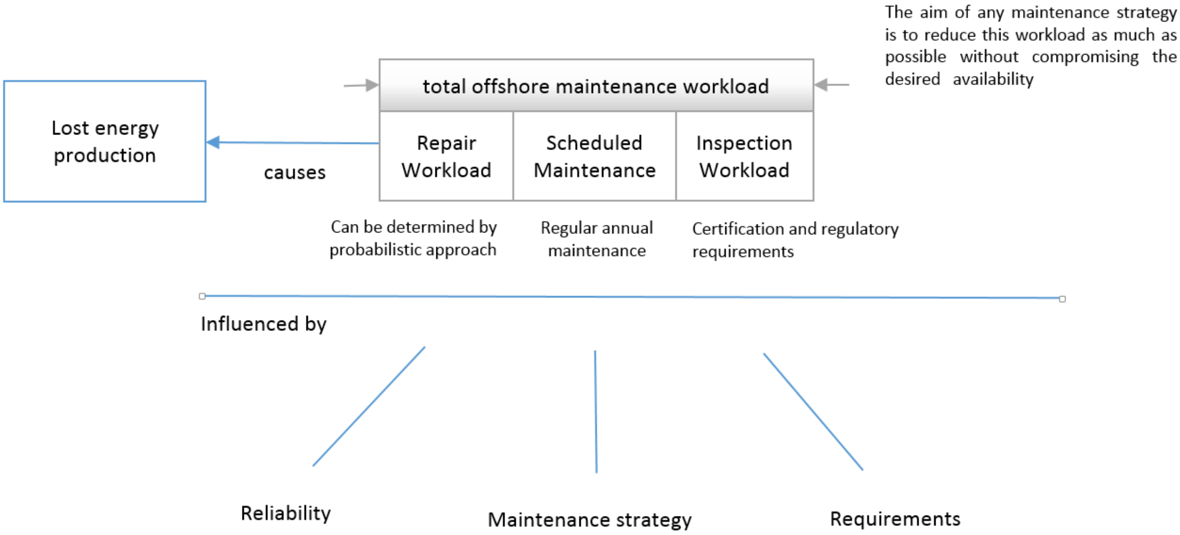

Figure 3-1: Offshore workload composition overview for a regular wind farm

To be in line with the chosen approach to focus on a planned maintenance methodology and to cater for an 'onshore' and 'on-site' strategy the workload has to be divided. The corrective maintenance or repair workload typically is determined by a probabilistic method with average failure rates. In both cases, for the 'on-site' and 'onshore' service strategy, the corrective maintenance workload will be considered as a constant. Adding to the above approach is the fact that corrective maintenance would not be effected by the floating technology. Corrective maintenance for floating wind farms will be performed in the same manner as for fixed wind farms. That means that in the most cost effective manner and in an ASAP fashion to reduce the amount of lost production. Therefore, the following approach is chosen: All corrective activities are excluded from the analysis. The total remaining maintenance workload, which will be looked at, results from the scheduled maintenance requirements as well as the workload for all inspection activities (see Figure 3-2).

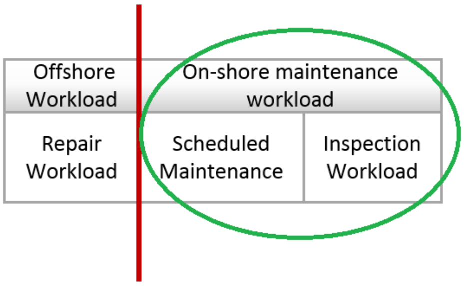

Figure 3-2: Onshore and on-site workload

To find the total workload resulting from the scheduled maintenance and inspection requirements, all the man-hours[7] are summed. This means that for every larger component of the FWTU the annual scheduled maintenance time in net man-hours are added to compute a total annual workload that has to be accomplished to maintain the wind farm. In the next step, the duration and resources needed to complete this workload with the 'on-site' and 'onshore' approach is computed. Linked to each case, there are two scenarios. In the first scenario, the maintenance workload is carried out in the wind farm, 'on-site'. This scenario always serves as a benchmark or baseline that the second scenario can be compared to. The second scenario then computes the cost for an 'onshore' service in which the FWTU is returned to shore. The different methods that have been applied for each strategy are described in the next section.

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[7] Unit measuring work: a unit that measures the amount of work that can be done by one person in one hour and the cost of that hour's work. (From Wikipedia: https://en.wikipedia.org/wiki/Man-hour. Accessed on 08.12.2015)

3.2.3 ‘On-site’ maintenance

In the ‘on-site’ maintenance case, this workload demand has to be accomplished underlying multiple restrictions. Looking at a monthly period the net available working time is given by the total amount of hours available per month. This number is reduced by the weather factor. The weather restriction is primarily determined by the chosen access system. For the crew transfer vessel and boat landing method of transferring the technicians to the turbine, the accessibility depends on the significant wave height H_{m0} and wave direction. Access is typical possible up to a wave height of maximum 1.5 m (Slengesol et al., 2010). The threshold for being able to perform work is then the significant wave height H_{m0} of 1.5 m. Every time this threshold limit is exceeded no work can be executed, since personal cannot be deployed.

When suitable weather conditions allow work to be carried out, the available working time duration within a shift from an individual technician is further reduced by the transfer, access and perpetration time. All those above effects can reduce the net available offshore working time by 50% (Slengesol et al., 2010). Even when only a fraction of the initial available man-hours (MH) remains, the cost per month don’t vary significantly because the vessels and salary expenses have to be paid regardless of the standby periods. This is displayed in Figure 3-3.

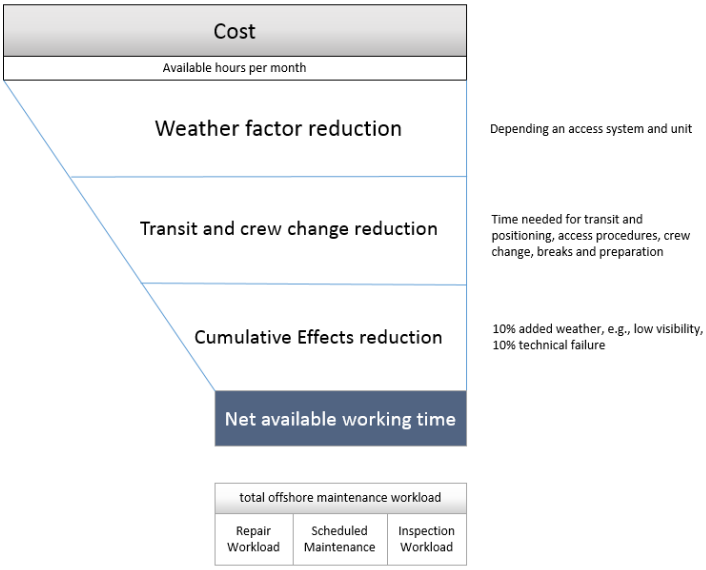

Figure 3-3: Net available working time computation

During the winter month, the weather conditions are general less favorable than in the summer. Therefore, it is useful to further break down to a monthly scale. If we now also apply the fact that no corrective repair will be taken into consideration we will get the following overview (Figure 3-4). To cover the annual maintenance workload, the sum of the net available working time has to match this man-hour demand for the annual required maintenance workload.

$$\sum \mathit{Net\ available\ working\ time} = \sum \mathit{Total\ annual\ required\ maintenance\ workload}$$

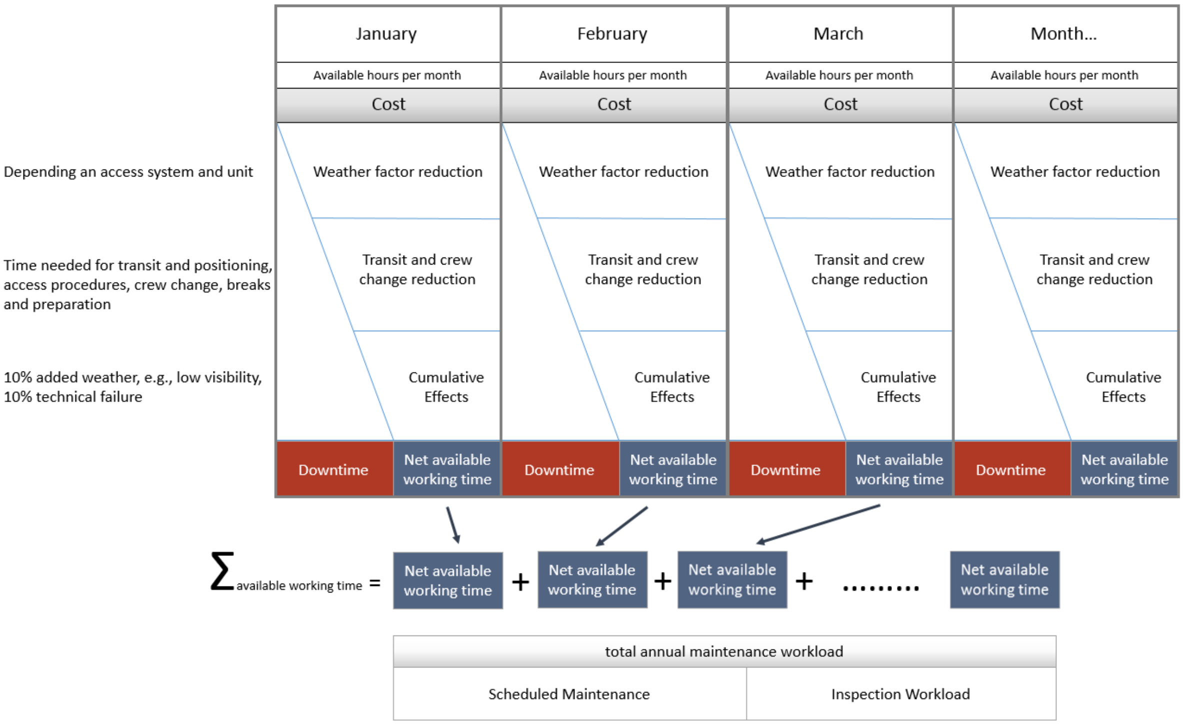

Figure 3-4: Computation schematic for the ‘on-site’ maintenance strategy

If we now assign the resources required to deliver the net available working time (NAWT). We can compute the actual duration and hence resources and cost needed to ensure that the maintenance workload in an ‘on-site’ maintenance approach is covered.

3.2.4 ‘Onshore’ maintenance

The ‘onshore’ strategy is approached in a similar fashion, but taking into account the different specifications this strategy requires. Again only, the exact same annual maintenance workload demand used for the ‘on-site’ maintenance approach is looked at. Reactive repairs are not included, only the scheduled and inspection workload. For the onshore maintenance, hardly any weather restriction apply, so the available working time equals the maintenance workload time. However, the duration for the T&I process for returning the FWTU to shore has to be included into the cost calculation. This period will be weather restricted. The restrictions in the ‘on-shore’ approach are resulting from the weather restriction for the marine operations required for the T&I phase or towing the FWTU back to shore or the wind farm. Of course, the weather restrictions are adapted to the limits, which apply for the specific marine operation and there’re differ from the weather restrictions used for CTVs in in the previous set up.

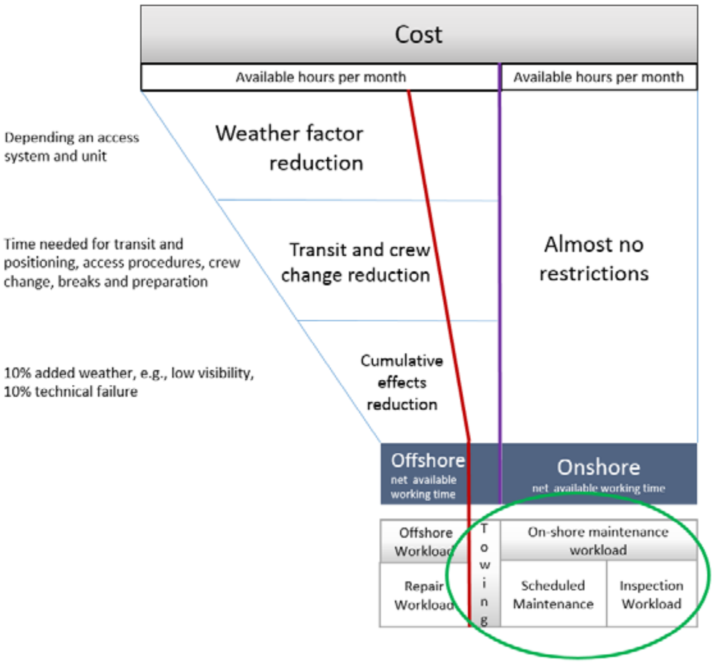

Figure 3-5: 'Onshore' computation schematic

To compute the duration of the Transport and Installation (T&I) process of the semi-submersible wind turbine a detailed work break down structure (WBS) was developed. All possible sources for information were used to build this WBS. Papers and presentations describing the WindFloat demo project were the main source of information (C. Cermelli, Roddier, & Weinstein, 2012). Pictures, conference presentations and expert interviews provided additional input. If no data was available assumptions based on experience from similar operations and good judgment were made. Some weather restriction for the towing operation could be taken from stated literature. In addition, the pictures from the installation of the WindFloat 1 in Portugal provided valuable input to the number and types of vessels used as well as to the sequence of the installation activities. In this report T&I is referred to as the processes of towing the turbine to the wind farm site and installing it at its location.

This includes:

- Float out & towing preparation
- Transit to wind farm site
- Hook-up and tensioning of mooring system
- Cable installation
- Cable termination
- Commissioning

The temporally decommissioning or disconnecting of the FWTU and returning it to shore for maintenance is considered to be part of the T&I process and hence forward referred to as transport, installation and maintenance (TI&M).

TI&M therefore also includes:

- Shutdown and sea-fastening preparation
- Cable disconnection
- Disconnecting of the mooring system
- Tow in

Likewise, for the workload computation the, for every process step of the TI&M process of towing the turbine back to shore or returning it to the wind farm at a later stage, the durations and weather restrictions were assigned and the total duration computed at the end. With the duration and main weather restriction identified, it was possible to compute the time and resources needed to return all the turbines to shore.

The findings generated with the help of the WBS for the two-in and tow-out operation or TI&M process are presented in detail in section 5.1 or in **Appendix B**.

Chapter 4

4 Casestudy and input paramters

4.1 Parameter

In this chapter all the parameters that were utilized as input for the MS-Excel model are presented. Real metocean data was used for the computation of project duration and downtime periods, but parameters such as wind farm size (400-MW) and turbine size (5-MW) were selected to represent a realistic but assumed wind farm. Since no large scale floating wind farm exists which could serve as a reference project, one (1) representative but hypothetical wind farm had to be defined. To further evaluate, the influence that altered distances to shore have on the two (2) different maintenance strategies, three (3) case were determined with varying distances from the coast. Then the maintenance workload had to be computed. A detailed description is given in section 4.4 of this chapter. Various marine operations ranging from simple personnel transfer (PT) to complex cable pull-in and towing operations had to be studied. Detailed information about the duration, weather restriction and assumptions in respect to those procedures are also given in this chapter. Finally, yet importantly, the cost data, the feed in tariff and energy production computation is explained. It was foreseen that assumptions had to be made since information is not easily accessible without an industry partner and an actual project. In case assumptions had to be made, they were verified in expert interviews to ensure that they are close to the current industry norm.

4.2 Wind farm

The wind farm used as a reference for this study is a hypothetical set up. Still, the aim was to have a very realistic plant that reflects the current industry standard. Defined project size is 400 MW from eighty (80) offshore turbines with a rated capacity of 5 MW each. The wind farm is located in the North Sea in a location suitable for floating foundations. The wind turbine generators are installed on WindFloat substructures. The water depth is greater than 50 m. Only the turbine O&M cost is simulated, hence BOP components like the offshore substation and the infield cabling are not further specified. They also will not be included in the computation. To understand the impact, the distance to shore has on each maintenance approach, 3 different cases with varying distances have been defined. The 'nearshore' case with a total distance of 20-NM (~37 km) off the coast. The 'offshore' case is located 35-NM (~65 km) and the 'open ocean' case with a total distance off coast of 50-NM (~93 km). The wind farm parameters are summarized in Table 4-1.

Table 4-1: General data and assumptions about the wind farm

Name	Value	Description
Location	North Sea	
Park size	400 MW	Delivered to onshore grid or HVDC connection
Lifetime	20 years	The technical lifetime of the power plant
WTG in the farm	80	Number of turbines installed
WTG description	Rated Power = 5 MW Hub height = 90 m 3 blades	
Converter platform	1	Floating, all infield cables are bundled here
Distance to shore	Between 50 km and 200 km	
Water depth	From 50 m	
Met-Ocean conditions	German Bight	

5 MW turbines are widely used in current offshore projects now and can be considered the industry norm. This especially hold true for projects located further off coast in water depths ranging from 30 m to 50 m. At this stage, the turbine is not further specified.

4.3 Cases and scenarios

To study the impact, the distance to shore has on each maintenance approach; three (3) different cases with varying distances have been defined. The 'near-shore' case with a total distance of 20 NM (~37 km) from the coastline. The 'offshore' case is situated 35-NM (~65 km) off coast and the 'open ocean' case with a total distance to shore of 50-NM (~93 km). The names and the assigned distances used to class the cases are no official definition. They have been inspired by the classing system defined for aquaculture systems in 'Farming the Deep Blue' by James Ryan (2004). The distances have been altered to match the natural requirements for offshore wind farms. The 'near-shore' site is situated 20-NM from the coast. Linked to each case, there are two scenarios. In the first scenario, the maintenance workload is carried out in the wind farm, 'on-site'. This scenario always serves as a benchmark or baseline which the second scenario can be compared to. The second scenario then computes the cost for an 'onshore' service in which the FWTU is returned to shore.

Within the 12-NM zone multiple interests from different stakeholder (e.g. Fisheries, nature conservation areas, waterways, etc.) can make it very difficult to approve a wind farm inside the 12-NM zone. For these reason the value of 20-NM was selected for the 'near shore' case. The service hub is onshore based and the technicians are transported to the wind farm and access is made possible with CTV's.

In the 'offshore' case, the wind farm is located 35-NM from the closes harbor. As stated in section 2.4.2, there is a 'transition point' from onshore based to offshore based maintenance due to the increasing transit and reduced working time. This is said to be around forty (40) nautical miles (NM) from the nearest service hub. Thus, the case two (2) offshore wind farm is situated 35-NM from the coastline. Again, an onshore-based service hub was selected. Technicians are transferred to the wind farm site by CTVs.

Present day, a small number of wind farms, located 50-NM from the coast exist. For these projects, the onshore-based service approach is not applicable any more. Transit times become so large that hardly any working time per work shift remains. To investigate if the floating foundations can offer an O&M advantage for such wind farms a 50-NM case has been included in the analysis. Since the onshore-based service approach for the baseline scenario in the 50-NM case is not realistic, a different set up for the third case had to be chosen. As an alternative, a ship-based maintenance approach was selected. In general, a platform-based approach is also possible. However, it was difficult to properly assign costs for such an approach. The converter platform or offshore substation is in those cases equipped with living quarters to house the service personnel. This multi-use of the structure made it difficult to split and assign costs to the baseline scenario. Therefore, the ship-based approach was chosen, even though it is believed that it involves higher costs.

4.4 Maintenance Workload

Detailed annual scheduled maintenance workload statistics for 5-MW offshore turbines are not available. Literature only provided very broad values, ranging from 190 hours up to 400 hours scheduled maintenance per WTG structure and year (LLC, January 2015). From personal experience, a value of 220 hours is known. In order to obtain a more specific value for the annual service time, which could be used in the analysis, the following approach was chosen. In compliance with the GL Guideline[8] for the certification of offshore wind turbines the WTG and the semi-submersible substructure was subdivided into the individual components and systems. Similar to the SFI group system (SFI: Skipsteknisk Forskningsinstitut, 1972) the components and systems were organized in different groups. In the next step, the net service time for each group, sub-group or component was allocated. The assumptions were then verified in expert interviews with service engineers from two (2) major turbine manufactures. They confirmed or corrected the duration of the preliminary maintenance times of each component. In the cases when no data was available, assumption based on the authors experience were made. All these individual service times have then been added up. The total duration amounts to 192.5 net man-hours. Table 4-2 displays a summarised overview of the different service times for the FWTU. The detailed workload computation can be found in **Appendix A**.

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[8] GL Guidelines for the certification of offshore wind turbines GL_IV_2-1-13_e_Edition2012

It was paid special attention to ensured that only net working hours were counted. Time for job preparation or breaks were not taken into account. Hence, the 192.5 hours represent the annual net man-hours of scheduled maintenance and in-service inspection time required to maintain a single floating wind turbine unit. This sum will serve as the baseline value to compute the O&M cost for the two (2) different strategies.

Depending on the original equipment manufacturer (OEM), most turbines require some form of larger overhaul every fourth (4th) or fifth year (5th) year in addition to the annual workload. It was not possible to get any specific information on the workload or duration of such an overhaul. This might partially be to the fact, that not many 5 MW turbine have reached such an age yet. It was therefore assumed that the workload for the major 5th year overhaul is 220 man-hours in addition to the 192, 5 hours' annual service workload.

Table 4-2: Service workload overview

No.	Main group	Group	Net service time [h]	Remarks
1.0.0	[1] WTG			
1.1.0		[1] In-service inspection	5	
1.2.0		[2] Structures	29	
1.3.0		[3] Machinery Components	29	
1.4.0		[4] Electrical Installations	32	
1.5.0		[5] IT, Control & Communication	5	
1.6.0		[6] Safety	10	
		Sum WTG	110	
2.0.0	[2] Floating Substructure & Tower			
2.1.0		[1] In-service inspection	13	
2.2.0		[2] Station Keeping	16	
2.3.0		[3] Secondary Steel	9	
2.4.0		[4] Mechanical	8	
2.5.0		[5] Corrosion Protection	11	
2.6.0		[6] Electrical Systems	3	
2.7.0		[7] Other	22,5	
		Sum Substructure	82,5	
		Total FWTU	**192,5**	
3.0.0	[3] Subsea Installations	Not included		
4.0.0	[4] 5th year major overhaul	Sum Overhaul	220	

For the fifth year, service overhaul the aim was to handle the additional work with the same resources used in the regular year by extending the project duration into the winter month. If it was not possible to complete the workload with the existing resources in the same year, additional vessel and resources were allocated gradually. This was then repeated so long until the net man-hours delivered from the assigned resources matched the required service hours' demand. Due to weather restrictions, the monthly obtainable net man-hours vary strongly. This required to manually distribute the man-hours demand over the year and month.

4.4.1 Turbine

The computed annual service workload for the WTG is hundred ten (110) man-hours. The three (3) largest contributors to the WTG maintenance workload are the machinery and electrical components and the structure itself. The sub groups and components and the correspondent service times from the three (3) groups are listed in Table 4-3. The detailed overview covering all groups can be found in **Appendix A**.

Table 4-3: Groups, sub-groups, and corresponding maintenance times

Machinery components	[h]	Electrical components	[h]	Structure	[h]
Blade Pitching Systems	6	Power Transformer	1	Rotor Blades	18
Bearing & Gearbox	5	Frequency Converter	3	Machinery Structures	5
Gearbox		Medium-voltage Switchgear	2	Nacelle Covers and Spinners	2
Mechanical Brakes & Locking Devices	2	Back-up Power Supply Systems	1	Tower connections	4
Couplings	2	Low Voltage Switchgear; Control gear and Switchboards	1		
Elastomer Bushings	1	Cables, Lines and Accessories	3		
Yaw Systems	3	Lightning Protection	21		
Hydraulic Systems	2				
Lifting appliances	8				
Lift	5				
Total	**29**		**32**		**29**

Electrical systems like the power transformer (33kV and 3kV) do not need a lot of maintenance. A large amount of service time is allocated to the bolted connection maintenance and the in-service inspections from certification requirements. The blade inspection, mostly done with rope access is a very time-intensive undertaking with high weather restrictions. Wind speed must be low that the climbers are able to work on top of the turbine. Maintenance and inspections work cannot be done in parallel.

4.4.2 Substructure

The annual service workload for the WindFloat substructure is computed in the same way. Only two (2) floating prototype structures are in operation now. Hence, experience values from existing projects are not available. The structure again was subdivided into the main groups and modules. For each system, the required service time was then assigned and components specific for floating platforms were added. In the case of the WindFloat that comprises the passive ballast system, the active ballast system and the chain jacking system. Experience values from similar system (bottom fixed foundations) and estimates made by professionals were used to find the total service time of 82.5 net man-hours per year. This approach is believed to deliver the best estimate at the moment, with no access to first hand data from the prototypes.

4.5 Weather restrictions and metocean conditions

The meteorological and oceanographic data used in this calculation is taken from metocean report compiled by the Danish Hydraulic Institute (DHI) for the offshore wind farm project 'Deutsche Bucht' und 'Veja Mate' (Danish Hydraulic Institute, 2009). This report contains a series of significant wave heights and wind speed in 30 minutes' time intervals. This data set is based on hindcasted data for a 29-year long period for a site[9] in the German bight of the North Sea. The report provides information on the monthly variation of weather windows and downtime periods given as a mean value in percentage for the entire 29-year period of data (Danish Hydraulic Institute, 2009).

A **weather window** is defined as:
A continuous period of time during which the significant wave height H_{m0} or the wind speed (m/s) is constantly below a given threshold value.

A **downtime period** is in the same way defined as:
A continuous period of time during which the significant wave height H_{m0} or wind speed (m/s) is constantly above a given threshold value.

This implies that for a given threshold value of significant wave height, e.g. H_{m0} of 1.5 m the analysis splits the 29-year long time series into alternating periods of weather windows and downtime periods falling below (weather window) or exciding (downtime period) the threshold. The data is given as percentage values for weather windows and downtime for each of the 12 month and for different value of the threshold significant wave heights H_{m0}. The given percentage therefore is a mean value based on the entire 29-year period of data. Therefore, divergences from this average values must be taken into consideration.

Example:
When looking at a regular 12-hour offshore work shift, a suitable weather window to deploy the technician to a location should have the same persistence (i.e. duration) as the duration of the work shift.
Further the weather restriction or threshold values for personnel transfer (PT) via CTV is H_{m0} = 1.5 m. To evaluate on how many days of a certain month maintenance activities are possible, the matching weather window for H_{m0} = 1.5 m and a persistence greater 12 hours has to be selected. For the month of January and a persistence greater 12 hours and for threshold value of Hm0 = 1.5m we obtain 35%. From this percentage, we now know that on 10.9 out of the 31days in January PT via CTV could be performed. This is referred to as the operational time given in Days (see Table 4-4).

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[9] 54° 19′ 1″ N, 5° 52′ 15″ O

Table 4-4: Weather windows

Hs 1,5 m / Persistence > 12 h DHI incl. 25% downtime (10% added weather, 10% technical failure , 5% crew change)														
Month			January	February	March	April	May	June	July	August	September	October	November	December
Weather Windows			35%	42%	48%	69%	74%	75%	77%	72%	57%	43%	36%	35%
Days			31	28	31	30	31	30	31	31	30	31	30	31
Operational Days (without additional downtime)			10,9	11,8	14,9	20,7	22,9	22,5	23,9	22,3	17,1	13,3	10,8	10,9
Additional downtime	10% Cumulative weather	10%	8,1	8,8	11,2	15,5	17,2	16,9	17,9	16,7	12,8	10,0	8,1	8,1
	10% Technical failure	10%												
	5% Crew change and delays	5%												
Weather Factor			3,81	3,17	2,78	1,93	1,80	1,78	1,73	1,85	2,34	3,10	3,70	3,81
Operational Days [d]			8,1	8,8	11,2	15,5	17,2	16,9	17,9	16,7	12,8	10,0	8,1	8,1
Operational Time [h]			195	212	268	373	413	405	430	402	308	240	194	195

$$Operational\ Time\ [d] = \left(D_{January} * WW_{January}\right)$$

Where:

$D_{month} = Days\ per\ month$

$WW_{month} = Weather\ Window\ of\ the\ month\ given\ in\ \%$

The weather data presented in the DHI report only contains information based on wind speed and wave height. Experience from past projects suggest that the actual downtime is slightly higher. This is mainly because the data does not take cumulative weather conditions like low visibility, icing and lightning into consideration. Hence operations might be possible but still prohibited due to the other weather phenomena. Consequently, an additional 10% (cumulative weather) of the remaining working time was subtracted. From this value further times was subtracted to cater for technical failures, crew changes, refuelling and maintenance of the vessel (See figure 3-3). From this net remaining operational time, it was now possible to determine how many PT operations per CTV could be performed in January. The data from the DHI report was imported into the MS-Excel model for each required weather restriction resulting from the various marine operations. Using the weather factor obtained from the above-described calculation, it was now possible to compute the available time per month, which certain marine operations could be carried out.

4.6 Marine operations and vessel data

For the chosen cases and the scenarios, the following vessel have been selected in line with best engineering judgment and common industry practice. They are believed to be the most suitable option for the respective tasks. In addition, various marine operations have to be looked at in this analysis. In this paragraph, all relevant vessels, marine operations and limitations used in the analysis are explained and listed in detail. The following vessels were selected:

- Crew transfer vessel-CTV (for transporting technicians between the wind farm and the service hub)
- Offshore support vessel-OSV (accommodation vessel for the offshore-based service strategy)
- Anchor handling tug supply-AHTS vessel (towing the FWTU to the wind farm location and back)
- Seagoing tugboats (positioning and manoeuvring the FWTU in the wind farm)

The related marine operations comprise:

- Personnel transfer (PT) with CTV
- Personnel transfer (PT) from OSV or AHTS
- Float out
- T&I of the FWTU
- Hook up of the mooring system
- Cable installation

The most frequent marine operation in most wind farms are the personnel transfer (PT) operations. CTVs are commonly used. They typically have a capacity of 12 passengers, two (2) crewmembers and additional deck space for luggage, tools and smaller spare parts. A large fender is installed at the bow of the craft. To allow personnel to disembark and step-over from the vessel to the substructure of the wind turbine, the vessel is positioned in front of the boat lending. As soon as the fender from the CTV is docked to the fender poles of the boat landing, full thrust ensures that the bow of the craft is pressed against the boat landing and that the CTV holds its position. This depends on wave height, typically PT with CTVs is possible up to a maximum H_{m0} of 1,5 m (Slengesol et al., 2010). Average cursing speed used in this analysis is 20-kts (Maples et al., 2013). Transit times to the wind farms can be seen in Table 4-5.

Table 4-5: Crew transfer vessel (CTV) specifications

Specification	Value	Remarks
H_{m0} max	1.5 m	Taken from (Slengesol et al., 2010)
Speed	20kts	Assumed average speed for CTV vessels used in all calculations
Travel time Case 1 (20-NM)	1h	
Travel time Case 2 (35-NM)	1,75h	
Travel time wind farm	30 min	30 minutes for park transit since the CTV hast to deploy multiple teams
Passenger capacity	12	Industry standard
Day rate	3000 €	Estimate from past experience, depends on market conditions

In the offshore-based service scenario, an OSV serves as the mother vessel for the technicians in the wind farm during the service campaign. Access to the turbine is done with a motion-compensated gangway like the Ampelmann or Uptime system (Figure 4-1). Especial when modern ships with X-Bow hull shapes are used, such a set-up can achieve good access performance values of up to H_{m0} =2,5 m or higher. The limiting factor in most cases becomes the number of PT operations the vessel can facilitate in a 12 hours period. For transits between any location within the wind farm experience shows that it is safe to assume 1 hour. Positioning time depends on many factors (Vessel type, DP equipment, weather condition and DP crew experience) and is defined to be 40 minutes per location. The PT operation itself and transfer of equipment and material is included. This allows seven (7) teams being deployed at different locations within the wind farm before the first team hast to be collected/ exchanges due to the end of their shift. The special challenge with this kind of approach is that, the weather has to be monitored very closely, to always be able to gather all the teams again before the weather restrictions for the PT operation are passed. The OSV, complimented by a motion compensated gangway set-up delivers very good performance values in respect to delivering a large number of man-hours to the turbine with very low weather downtime. As a result, it is well suited for scheduled maintenance campaigns. However, it comes with a relative high price tag compared to the other approaches.

Figure 4-1: OSV Siem Moxie during Uptime operation, source: (www.uptime.no)

Table 4-6: Offshore support vessel (OSV) specifications

Specification	Value	Remarks
H_{m0} max	2.5 m	
Speed		Not relevant
Travel time	1h	Average transit time between any two location within the wind farm
DP time	40 min	Time required to position the vessel close to the turbine
Passenger capacity	40	Industry standard
Day rate	€ 67810	Estimate from past experience

Anchor handling tug supply (AHTS) vessel are used to transport and install the FWTU. This involves towing the unit from the onshore assembly and service hub to the wind farm location. For a large-scale floating wind farm it is assumed that the hook up and commissioning teams are accommodated on the vessel. Access can again be via a motion-compensated gangway. The restriction can be assumed similar to the ones from the OSV vessels even though when AHTS are generally of smaller size. According to the reviewed literature and interviews the weather restrictions for the towing are stated to be 2,5 m (C. Cermelli et al., 2012). Due to good stability performance of the semi-submersible, this might very well be true for the towing operation itself. In this report the hook-up and tensioning of the mooring system is considered an integral part of the T&I process. A realistic value for the wave height threshold such works can be performed is assumed to be at maximum significant wave height of H_{m0} = 2m. Therefore, this more conservative value will be utilised as the main overlying restriction for the whole T&I process.

Table 4-7: Anchor handling tug supply (AHTS) vessel specifications

Specification	Value	Remarks
H_{m0} max	2 m	Access and towing restriction
Speed	3kts	Towing speed (C. Cermelli et al., 2012)
Transit time 20-NM	7h	Towing time between wind farm and onshore base
Transit time 35-NM	12h	
Transit time 50-NM	17h	
TI&M process time	6-7d	
Passenger capacity	~ 40 pers.	
Day rate	36100 €	Estimate. Daily Costs all incl.(Bunker cost, Ampelmann 24/7, catering)

To maneuverer and position the FWTU within the wind farm, it is assumed that two (2) additional seagoing tugs are required. The tugs are only included in the cost computation and hence not further specified. During the time FWTU are returned to shore for maintenance they are permanently stationed offshore. They remain within the wind farm and always assist during the hook-up operation. The cost for the tugboats (Daily costs all incl. 5990 € per tug) has been included in the model.

Returning a semi-submersible wind turbine to shore, maintaining it, and towing it back to its original location takes between six (6) to seven (7) days (depending on the distance to shore). The duration for completing one (1) TI&M process loop therefore exceeds the duration of the total FWTU maintenance time (~3 days, 24h, team size 5 pers.). Hence, the maintenance workload will be completed before the next turbine is brought back. If suitable weather conditions prevail, turbines can be constantly towed-in and back out in a continuous manner. This means that the newly arrived FWTU will be maintained while the vessel is returning one (1) unit to the wind farm. As soon as the vessel returns with the next FWTU, the maintenance activities on the current WTG will be completed.

The vessel cost presented are from personal experience backed by interviews with people working in the industry. Values strongly depend on various conditions like the duration of the contract (e.g. long-term charter vs. short-term). The vessel market is also strongly influenced by the general market situation and the demand for ships. This can have huge effects on the charter rates. The presented values therefore must be treated as rough estimates.

Vessel cost include the charter rate and bunker consumption and prices. In addition, the accommodation and catering cost for the service technicians are added depending on the total passenger numbers required for each operation. Additional expenses for operating a motion compensated gangway like the Up-Time system are included as well.

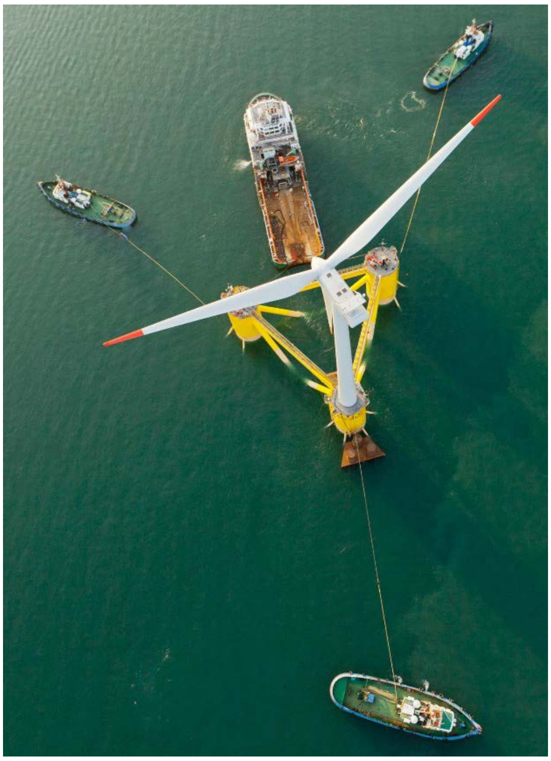


Figure 4-2: WindFloat during Tow-out, source: (Principle Power)

4.7 Energy Production

Energy production and respectively lost production is of great concern for every wind plant operator. The objective to optimize the amount of generated electricity for sale, at the smallest possible cost, is the fundamental basis for all decisions (Slätte & Ebbesen, 2012). Therefore, the effects that the O&M strategy has on the energy production cannot be neglected.

No specifies turbine data was available to compute exact power generation values based on weather data. A simplified approach was chosen, to compute values for this analysis. The rated power times the annual full load hours provided the annual energy production. With an assumed feed in tariff of 14 €-Cents per kilowatt-hour the hourly revenue from generated electricity per WTG is 304 Euro.

Table 4-8: Input data to calculate production and revenue

Parameter	Value	Remarks
Rated Power	5 MW	
Wind turbine power curve	Similar to NREL 5MW reference wind turbine	(Maples et al., 2013)
Cut-in & cut-out wind speed	3 m/s, 25 m/s	(Dinwoodie et al., 2015)
Feed in tariff	14 Ct/kWh	EEG 2014
Full load hours	3800	(Böttcher, 2013)
Availability	95%	(Slengesol et al., 2010)
Average wind speed	8 m/s	at a hub height of 90 meters
Annual energy production	19.000.000 kWh/a	Full load hours * rated power
Daily revenue per WTG	€ 7 288	
Hourly revenue per WTG	€ 304	

If a turbine is undergoing service, it cannot be assumed that the turbine will be able to run between or in parallel to the maintenance activities. Hence, if there are nine (9) weather windows in a specific month, and this period is booked with maintenance work, there will be work performed on the turbine. Hence, one can assume that the workable days per turbine times the available number of teams working. This will deliver a good estimate of the lost production. This approach also slightly takes into account that work will be carried out on the days when access to the turbine is possible and energy production can generally be expected to be lower. This is of course a very generic approach that can be challenged, however it is believed that it best correspondents with the line of investigation.

4.8 Assumptions and simplifications

Further assumptions and simplifications had to be made, in order to carry out the modelling in the MS-Excel tool. They are listed in Table 4-9.

Table 4-9: Overview of additional assumptions

Input Parameter	Value	Assumptions & Definition
Team size CTV	4	12 passengers per CTV, 3 teams with 4 technicians
Team size OSV	5	35 passengers and 7 PT operations in a 12h shift
Labour cost offshore	1200 €	Price per day for (€/day) for 12h shift. Includes personal protective equipment and training
Labour cost offshore	800 €	Price per day for (€/day) for 12h shift. Includes personal protective equipment and training
Spare parts		Assumed to be similar in both strategies, therefore not considered
Repair duration		Teams are assumed to work on one location per day. Maintenance task cannot be conducted in a parallel fashion.
Lost production		No energy production during maintenance
Simulation period	5 Years	4* regulars service and 1 year with increased workload due to the major overhaul
Currency	€	All prices and cost estimates are given in euro

Team sizes of 4 to 5 technicians are common in the industry and are assumed for this simulation as well. For reactive repairs, smaller teams of three (3) technicians might be the norm. The assumed team size was adapted to match then the specific vessels and strategy. In case of an accident a teams of four (4) or five (5) team members are better able to handle a patient on the WTG. Furthermore, the larger team size reduces the number of PT and supplies more net man-hours per turbine in one (1) PT operation. Team sizes larger than five (5) are not common, since the safety and rescue equipment on the turbine is limited. Only when a Jack-up or a vessel is on standby or additional equipment is brought to the turbine larger teams can work at the same time on one (1) location.

One additional assumption that had to be made, is in respect to the infield cable set up of the wind farm. It must be designed in such a way, that FWTU can be disconnected without effecting the other WTGs in the same cluster. If one (1) WTG is disconnected and returned to shore, it is assumed that the other turbines still connected to the same cluster are able to feed the generated electricity into the grid. In addition, the offshore substation must be designed to manage variable reactive power compensations.

Chapter 5

5 Results and Discussion

In this chapter a summary of the findings from the Work Breakdown Structure (WBS) analysis for the TI&M process as well as the simulation results are presented.

5.1 WBS Results

A solid understanding of them T&I process of a semi-submersible wind turbine was necessary to conduct the analysis. The information from the WindFloat 1 (C. Cermelli et al., 2012) installation was not sufficient to serve as input data for the study. The 24 hours period for the T&I processes stated in other sources was considers as a best guess and to optimistic. Hence an own estimate based on engineering judgment was developed using the WBS method. The WBS method was primarily used as a structured approach to get a better understanding of the T&I process steps involved when installing or returning a semi-submersible wind turbine to shore. Input values (e.g. weather restrictions, vessel requirements and durations) could thus be developed in an organised and comprehensible way. Apart from the input values, it delivered further results.

Table 5-1: WBS T&I process duration estimates

WBS main steps	Duration [h]	Comments
WBS TOW-Out		
Float out	10	Float out & Towing preparation
Transit	2,5	From shore to offshore location, towing speed 3nm/h, distance is case specific. + 7h / 12h / 17h
Installation	13	Hook-up and tensioning of mooring
Cable Installation	11	Pull in operation
Termination	22,5	Power connection, hang-off and testing
Commissioning	16	Remove transport lock & final WTG commissioning
Total duration	**75**	
WBS TOW-In		
Systems shut down	11	Transport lock and sea fastening preparation of FWTU
Cable Disconnection	19,5	
Disconnecting mooring	7	
Tow In	7	From the offshore location back to shore, towing speed 3nm/h, distance is case specific. + 7h / 12h / 17h
Total duration	**44,5**	

As the results from Table 5-1Table 2-1reveal, a fast amount of the total process time is allocates to install the cable and mooring connection of the semi-submersible wind turbine. The pull in of the sea cable and establishing the power connection has an estimated duration of around 33,5 hours. Hook-up and tensioning of the mooring system accounts for 13 hours. Hence, the duration required to transport and install a FWTU takes 75 hours. The time needed to return the turbine to shore is estimated to be 44,5 hours. This excludes the time for the transit itself. Since the duration of the transit time depends on the distance, this period hast to be added additionally. Possible transit times for the different cases that have been looked at in this report are:

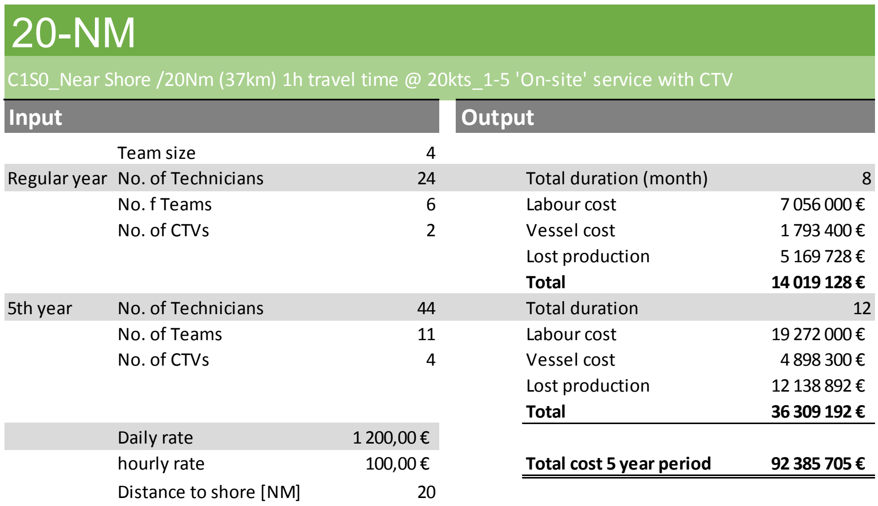
- 7 hours for the 20-NM distance at a towing speed of 3kts
- 12 hours for the 35-NM distance at a towing speed of 3kts
- 17 hours for the 50-NM distance at a towing speed of 3kts

From the tow-out & tow-in process analysis and the resulting time estimates, it becomes evident that the mooring and especially the cable connection procedure are currently strongly effecting the whole procedure. The computed values were used in the calculation for the O&M cost. The complete WBS can be found in **Appendix B**.

5.2 O&M cost simulation results

This section presents the summarised results for all three (3) cases and corresponding scenarios. The first case looked at the windfarm closest to shore (20-NM). Scenario zero (0) always represents the baseline scenario in which all maintenance work is done ‘on-site’. The results for Case1 Scenario0 (C1S0) are displayed in Table 5-2. Two (2) CTVs and 24 technicians were needed to complete the annual maintenance workload in a regular year. It required 8-month to complete all the tasks. In the 5th year the increased workload from the major overhaul required to increase the number of technicians and CTVs. With 44 technicians and four (4) CTVs it was possible to complete the workload in a 12-month period. The maintenance cost for a 5-year period amount to 92M Euro. Comparing the regular year with the 5th year service cost the price for vessel and lost production doubled were as the labour cost almost tripled. The largest contributor to the overall price the baseline scenario C1S0 are the labour costs.

Table 5-2: Case1 Scenario0 (C1SO) O&M cost estimate results

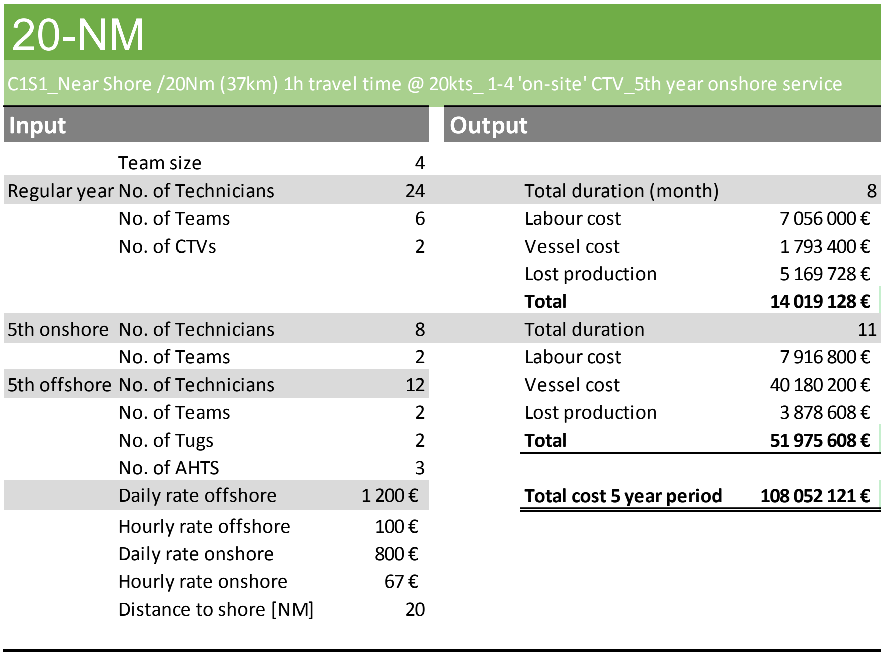


20-NM

C1S0_Near Shore /20Nm (37km) 1h travel time @ 20kts_1-5 'On-site' service with CTV

Input			**Output**	
	Team size	4		
Regular year	No. of Technicians	24	Total duration (month)	8
	No. f Teams	6	Labour cost	7 056 000 €
	No. of CTVs	2	Vessel cost	1 793 400 €
			Lost production	5 169 728 €
			Total	**14 019 128 €**
5th year	No. of Technicians	44	Total duration	12
	No. of Teams	11	Labour cost	19 272 000 €
	No. of CTVs	4	Vessel cost	4 898 300 €
			Lost production	12 138 892 €
			Total	**36 309 192 €**
	Daily rate	1 200,00 €		
	hourly rate	100,00 €	**Total cost 5 year period**	**92 385 705 €**
	Distance to shore [NM]	20		

Table 5-3: Case1 Scenario1 (C1S1) O&M cost estimate results



20-NM

C1S1_Near Shore /20Nm (37km) 1h travel time @ 20kts_ 1-4 'on-site' CTV_5th year onshore service

Input			**Output**	
	Team size	4		
Regular year	No. of Technicians	24	Total duration (month)	8
	No. of Teams	6	Labour cost	7 056 000 €
	No. of CTVs	2	Vessel cost	1 793 400 €
			Lost production	5 169 728 €
			Total	**14 019 128 €**
5th onshore	No. of Technicians	8	Total duration	11
	No. of Teams	2	Labour cost	7 916 800 €
5th offshore	No. of Technicians	12	Vessel cost	40 180 200 €
	No. of Teams	2	Lost production	3 878 608 €
	No. of Tugs	2	**Total**	**51 975 608 €**
	No. of AHTS	3		
	Daily rate offshore	1 200 €	**Total cost 5 year period**	**108 052 121 €**
	Hourly rate offshore	100 €		
	Daily rate onshore	800 €		
	Hourly rate onshore	67 €		
	Distance to shore [NM]	20		

The duration of the current TI&M procedure made it swiftly clear, that for the moment it was only meaningful to look at a scenario were the FWTU is returned to shore for the larger maintenance workload in the fifth year. Not only is the required time for TI&M to large, also the current technology level of the cables and mooring systems prohibits an annual onshore service approach. Therefore, the service in the first four (4) years was computed in the same way as in the baseline scenario. In the fifth year, the FWTU was then brought to shore for the regular and overhaul maintenance workload to be performed onshore.

The maintenance cost in the fifth year amount to 52M Euro compared to 36M Euro from the baseline scenario. Although the cost for labour and lost production reduce significantly, vessel cost increase by a factor of eight (8). Thus, the savings gained are lost and the total cost of the campaign exceed that from the baseline scenario

The second Case2 examined the wind farm set-up located 35-NM from the coast. Again, the same approach like in Case1 was applied. As well, Scenario0 represents the reference setting. Once more, the onshore based CTV approach was chosen. The predicted transition point form an onshore based approach to an offshore based setup is according to 'A Guide to UK Offshore Wind Operation and Maintenance' (GL Garrad Hassan, 2013) around 40-NM from the nearest service hub. Close to the 35-NM chosen for Case2. For that reason, this approach also represented a possibility to check the credibility of the computation method since it was expected that the values would reach impractical levels compared to an offshore-based service approach. Transit time (1,75h) already indicated that the results for such a set up could become impractical.

In compliance with the defined line of approaching each analysis, it was tried to complete the workload (regular year) with the same resources as in the Case1. Even though the transit time had increased, it was possible. However, it took 12 month compared to the 8 month needed in C1S0. This explains the increased cost of 20M Euro of the C2SO scenario, if compared to the 14M Euro from C1SO, even with identical resources used.

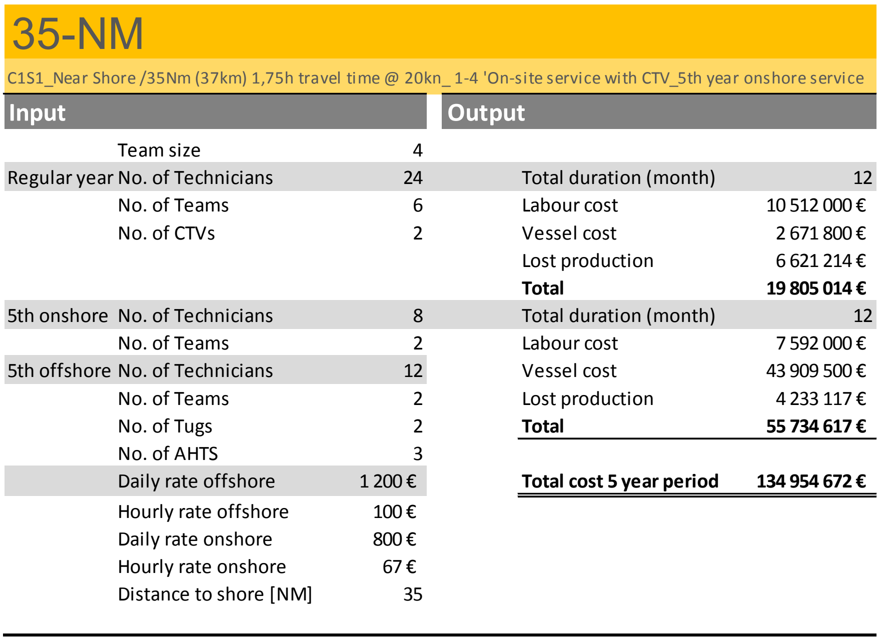
Table 5-4: Case2 Senario0 (C2S0) O&M cost estimate results

35-NM				
C2S0_Near Shore /35Nm (65km) 1,75h travel time @ 20kts_ 1-5 'On-site' service with CTV				
Input			**Output**	
	Team size	4		
Regular year	No. of Technicians	24	Total duration (month)	12
	No. of Teams	6	Labour cost	10 512 000 €
	No. of CTVs	2	Vessel cost	2 671 800 €
			Lost production	6 621 214 €
			Total	**19 805 014 €**
5th year	No. of Technicians	56	Total duration (month)	12
	No. of Teams	14	Labour cost	24 528 000 €
	No. of CTVs	5	Vessel cost	6 234 200 €
			Lost production	15 449 499 €
			Total	**46 211 699 €**
	Daily rate offshore	1 200 €		
	Hourly rate offshore	100 €	**Total cost 5 year period**	**125 431 753 €**
	Distance to shore [NM]	35		

In order to manage the 5th year service workload within one (1) year, resources had to be increased. 56 technicians and five (5) workboats had to be used to manage the workload. This lead to overall maintenance cost of 46M Euro in the fifth year and 125M Euro for the complete five (5) year period.

In Senario1, the turbines were return for onshore maintenance in the fifth year. It also required 12 month completing all maintenance task. This campaign did cost 56M Euro and 135M Euro for the whole five (5) year period.

Table 5-5: Case2 Senario1 (C2S1) O&M cost estimate results



35-NM

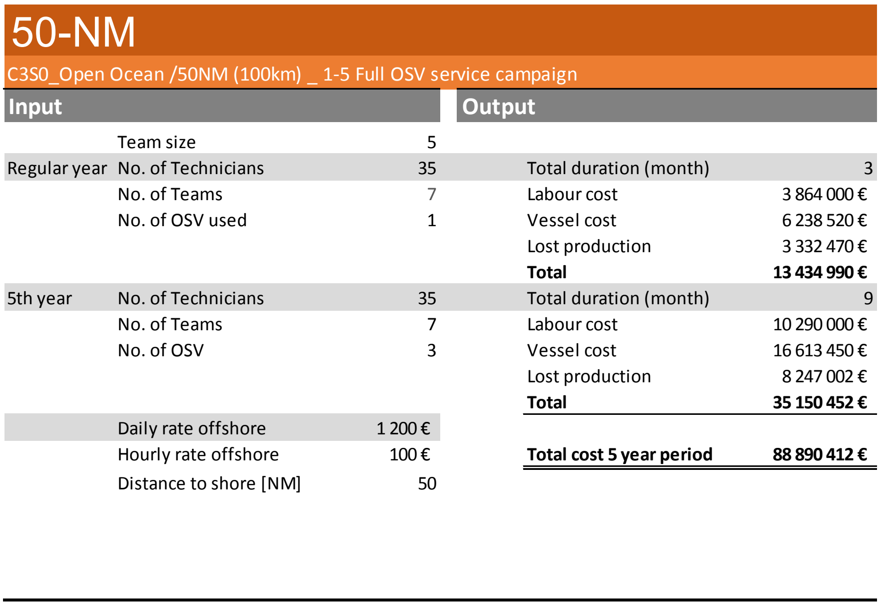
C1S1_Near Shore /35Nm (37km) 1,75h travel time @ 20kn_ 1-4 'On-site service with CTV_5th year onshore service

Input			Output	
	Team size	4		
Regular year	No. of Technicians	24	Total duration (month)	12
	No. of Teams	6	Labour cost	10 512 000 €
	No. of CTVs	2	Vessel cost	2 671 800 €
			Lost production	6 621 214 €
			Total	**19 805 014 €**
5th onshore	No. of Technicians	8	Total duration (month)	12
	No. of Teams	2	Labour cost	7 592 000 €
5th offshore	No. of Technicians	12	Vessel cost	43 909 500 €
	No. of Teams	2	Lost production	4 233 117 €
	No. of Tugs	2	**Total**	**55 734 617 €**
	No. of AHTS	3		
	Daily rate offshore	1 200 €	**Total cost 5 year period**	**134 954 672 €**
	Hourly rate offshore	100 €		
	Daily rate onshore	800 €		
	Hourly rate onshore	67 €		
	Distance to shore [NM]	35		

The third case examined the windfarm that was located 50-NM from the coast. Here the onshore-based service approach for the baseline scenario was not applicable any more. As the cost information for a ship-based strategy were straightforwardly available, this approach was preferred over the platform-based concept.

Due to the good accessibility performance provided by the OSV or ‘walk to work’ vessel and the higher number of net-working time per work shift, the regular workload could be accomplished in 3 month. The short duration positively affected the cost. Especially labour and lost production were low. The cost for the service campaign during a regular year amounted to 13M Euro. The 5th year service, with a duration of nine (9) month, did cost 35M Euro (Table 5-6).

Table 5-6: Case3 Senario0 (C3S0) O&M cost estimate results



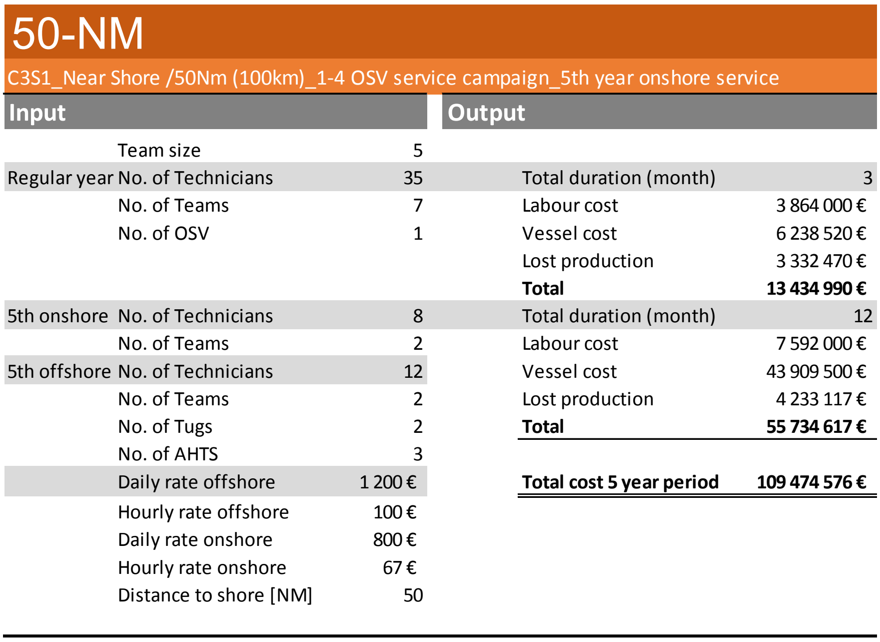
50-NM

C3S0_Open Ocean /50NM (100km) _ 1-5 Full OSV service campaign

Input			Output	
	Team size	5		
Regular year	No. of Technicians	35	Total duration (month)	3
	No. of Teams	7	Labour cost	3 864 000 €
	No. of OSV used	1	Vessel cost	6 238 520 €
			Lost production	3 332 470 €
			Total	**13 434 990 €**
5th year	No. of Technicians	35	Total duration (month)	9
	No. of Teams	7	Labour cost	10 290 000 €
	No. of OSV	3	Vessel cost	16 613 450 €
			Lost production	8 247 002 €
			Total	**35 150 452 €**
	Daily rate offshore	1 200 €		
	Hourly rate offshore	100 €	**Total cost 5 year period**	**88 890 412 €**
	Distance to shore [NM]	50		

Table 5-7 summarizes the results from the last Case3 Scenario1 (C3S1) grouping. The total of 56M Euros for returning the FWTU for onshore service, does not differ from the cost computed in C2S1. This is because the increased duration for towing does not significantly influence the total TI&M process duration and can be observed in all three (3) return to shore scenarios (S1). The resolution of the calculation is too coarse and therefore the time difference is not significant enough to contribute largely.

Table 5-7: Case1 Senario1 (C1S1) O&M cost estimate results



50-NM

C3S1_Near Shore /50Nm (100km)_1-4 OSV service campaign_5th year onshore service

Input			Output	
	Team size	5		
Regular year	No. of Technicians	35	Total duration (month)	3
	No. of Teams	7	Labour cost	3 864 000 €
	No. of OSV	1	Vessel cost	6 238 520 €
			Lost production	3 332 470 €
			Total	**13 434 990 €**
5th onshore	No. of Technicians	8	Total duration (month)	12
	No. of Teams	2	Labour cost	7 592 000 €
5th offshore	No. of Technicians	12	Vessel cost	43 909 500 €
	No. of Teams	2	Lost production	4 233 117 €
	No. of Tugs	2	**Total**	**55 734 617 €**
	No. of AHTS	3		
	Daily rate offshore	1 200 €	**Total cost 5 year period**	**109 474 576 €**
	Hourly rate offshore	100 €		
	Daily rate onshore	800 €		
	Hourly rate onshore	67 €		
	Distance to shore [NM]	50		

Chapter 6

6 Discussion and Conclusion

6.1 Discussion

The overall goal was to get a better understanding of the ‘return to shore’ service approach for FWTU and pinpoint improvement potential, which will support installation as well as operation and maintenance concepts for semi-submersible wind turbines. For that reason, the thesis aimed at evaluating if it is technically and economically feasible to return a floating wind turbine unit (FWTU) to shore to perform maintenance activities. The results presented in the previous chapter strongly indicate, that returning the turbines to shore on a regular bases is neither economically nor technical feasible.

While reviewing the TI&M process in the beginning, it quickly became clear, that the current technology level does not support such an approach. Therefore, the annual ‘onshore’ service is technically not possible due to current method of connecting the infield cables to the WTG. As stated in the very beginning of this report, it was regarded as an important principle of this study to compute robust results that would allow drawing evaluable conclusions. Hence, only the available technology was reviewed or considered. The current cable and connection technology is fully adapted to bottom fixed turbines. Cables only have to be disconnected in the low probability event of a cable failure. The current pull-in method, during which the cables are pulled into a J-tube through a Bell-mouth, connected to the pulling wire via a Chines Finger, expose high loads onto the first section of the cable. That requires shortening the cable afterwards. Hence returning the FWTU on a regular basis would require a considerable amount of additional cable length. That again, would lead to further complications. As a result, it was considered to be methodical not reasonable. Nevertheless, development and testing of subsea-connectors for ocean renewable energy converters and floating wind turbines is taking place and availability of suitable solutions can be expected within the next one (1) or two (2) years.

Henceforth, only the option to return the FWTU for the major overhauls in the 5th year was analysed, for varying distances of 20-NM, 35-NM and 50-NM to shore. The ‘onshore’ service or return to shore service approach was then compared to a realistic ‘on-site’ or offshore service strategy (baseline). The simulation results for ‘onshore’ service always exceeded the cost values of the baseline ‘on-site’ strategy. In respect to labour cost and lost production, the ‘onshore’ concept is competitive or even has lower costs then the baseline strategy. The relatively high vessel cost of the ‘onshore’ approach, however eradicate the savings from labour costs and lower lost production again and that is the reason for the higher overall costs of such a strategy. It could be noted, that the cost development is stable and hardly influenced by the distance to shore. It can also be assumed, that fewer influencing factors (e.g. less weather restrictions) make it a more plannable and stable task, compared to an offshore maintenance campaign.

Charter rates for vessels are highly fluctuating. At the current market situation, with a low oil price, it is believed that the vessel cost data utilised is relatively cheap. However, this cannot be quantified or confirmed. The used charter rates in this report are indicative of average values and should not be taken as absolute. Long-term vessel price development could be looked at in further studies, but this is not in the scoop of this paper. On the other hand, the mandatory vessels could be bought and included in the project CAPX. They then could be utilised during the construction phase, as well as for the maintenance of the mooring systems. This would reduce the cost far below the used charter rates that served as input for this analysis.

In addition, the workload for the underwater in-service inspection has not been included in this analysis either, as well as the maintenance workload for the mooring systems. It was not possible to gather sufficient reliable data to define a clear workload. This is mainly due to the reason that the floating wind turbine technology is still in the prototype and development stage and requirements are not yet specified.

The analysis also showed, that similarly to the cable topic the mooring systems has a noteworthy impact on the ease of installation of a floating wind turbine and the return to shore maintenance strategy. Current mooring systems used in floating wind applications have adopted Oil and Gas technologies. These were designed and optimised to maintain the integrity of flowline and risers for large multi-billion dollar installations. This mainly increases CAPEX costs. More importantly from an operational point of view is, to adapt and standardise the mooring technology to serve the requirements from floating wind turbine units. This will reduce complexity, shorten installation time and de-risk the hook-up procedures (Smith et al., 2015). This is supported by a paper recently published by Smith et al. (2015) at the EWEA conference in Paris (17-20 November).

The weather data used in the cost modelling of the O&M strategies is not from a location representative for a floating wind farm. This could be improved in a continuing investigation, by selecting data, e.g. from the northern North Sea. However, it represents an offshore wind farm location with the required distance from shore and exposure, hence is considered to deliver suitable results in respect to weather windows and downtime periods.

6.2 Conclusion and Outlook

Floating wind turbines have the potential to allow large-scale renewable energy projects, in areas where the bottom fixed technology is not possible. Yet, it will still take time and work until the technology reaches the full technical and commercial readiness. The aim of this paper is to support the idea of floating offshore wind technology by analysing if floating structures can support new and cost effective operation and maintenance strategies that involve ‘onshore’ service overhauls. This should reveal the culprits of such strategies and identify areas that need further development to support such strategies. The goal was to develop a better understanding of the ‘return to shore’ service approach for FWTU and its boundaries.

In general, it can be concluded that with the current technology level, returning a semi-submersible floating wind turbine for scheduled maintenance campaigns on a regular basis is not an economical and technical feasible approach.

Keeping in mind, that the floating wind turbine technology is still in the prototype and pre-commercial phase, this also concludes that there is still large potential for improvement. Distance to shore does not greatly influence the ‘onshore’ maintenance strategy, but the costs in general are not competitive to the cost of ‘onsite’ maintenance concepts. Reasons for this are the charter rates of the vessels required for the towing operations, as well as the total duration of the TI&M process itself. The current adaptation level of the mooring- and cables connection systems available to the market contribute to that. Mooring systems and dynamic power cable (including connectors) itself have been used in Oil & Gas projects but the technology needs to be adapted to cater for the requirements of floating substructures used, as a platform for WTGs. Systems similar to FPSO Type Turret connection might be a possible solution in offering a plug and play approach.

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Appendix A – Maintenance Workload

	Category				Number of FWEPU	Net repair time / WTG	Total net repair time
Work Group No.	Main Group	Group	Sub Group	Detail		[h]	[h]
1.0.0	**[1] WTG**				**80**	**110**	**8800**
1.1.0		**[1] In-service inspection**			**80**	**5**	**400**
1.1.1			periodical inspection of wind turbines	general visual inspection	80	0	0
1.1.2				close visual inspection	80	0	0
1.1.3				non-destructive examination	80	5	400
1.2.0		**[2] Structures**			**80**	**29**	**2320**
1.2.1			Rotor Blades		80	18	1440
1.2.2			Machinery Structures		80	5	400
1.2.3			Nacelle Covers and Spinners		80	2	160
1.2.4			Connections		80	4	320
1.3.0		**[3] Machinery Components**			**80**	**29**	**2320**
1.3.1			Blade Pitching Systems		80	6	480

1.3.2		Bearing	80	5	400
1.3.3		Gearbox	80		0
1.3.4		Mechanical Brakes and Locking Devices	80	2	160
1.3.5		Couplings	80	2	160
1.3.6		Elastomer Bushings	80	1	80
1.3.7		Yaw Systems	80	3	240
1.3.8		Hydraulic Systems	80	2	160
1.3.9		Drive Train Dynamics	80		0
1.3.10		Lifting appliances	80	8	640
1.3.11		Lift	80	5	400
1.4.0	**[4] Electrical Installations**		**80**	**32**	**2560**
1.4.1		Power Transformer	80	1	80
1.4.2		Frequency Converter	80	3	240
1.4.3		Medium-voltage Switchgear	80	2	160
1.4.4		Back-up Power Supply Systems	80	1	80
1.4.5		Low Voltage Switchgear; Control gear and Switchboards	80	1	80
1.4.6		Cables, Lines and Accessories	80	3	240
1.4.7		Lightning Protection	80	21	1680
1.5.0	**[5] IT, Control & Communication**		**80**	**5**	**400**
1.5.1		SCADA	80	2	160
1.5.2		Wi-Fi and Communication	80	1	80
1.5.3		Weather Station	80	2	160
1.5.4			80		0
1.6.0	**[6] Safety**		**80**	**10**	**800**
1.6.1		Fire Protection	80	2	160

1.6.2			Navigational lights		80	3	240
1.6.3			Lights		80	2	160
1.6.4			Safety Equipment		80	2	160
1.6.5			Survival Equipment		80	1	80
2.0.0	**[2] Floating Substructure & Tower**				**80**	**82,5**	**6600**
2.1.0		**[1] In-service inspection**			**80**	**13**	**1040**
2.2.0		**[2] Station Keeping**			**80**	**16**	**1280**
2.2.1			Jacking Systems	Regular Maintenance	80	8	640
2.2.2			Active Ballasting System	Regular Maintenance	80	8	640
2.3.0		**[3] Secondary Steel**			**80**	**9**	**720**
2.3.1			Heli Hoist	bolt pre-tension	80	2	160
2.3.2			Boatlandig	bolt pre-tension	80	3	240
2.3.3			Access platforms	bolt pre-tension	80	3	240
2.3.4			J-Tubes and Cable hang off	?	80	1	80
2.4.0		**[4] Mechanical**			**80**	**8**	**640**
2.4.1			Crane Outside	Regular Maintenance	80	4	320
2.4.2			Crane Inside	Regular Maintenance	80	4	320
2.5.0		**[5] Corrosion Protection**			**80**	**11**	**880**
2.5.1		Corrosion Protection **Active**	ICCP	Regular Maintenance	80	2	160
2.5.2		Corrosion Protection **Active**	Anode	Regular Maintenance	80	1	80
2.5.3		Corrosion Protection **Passive**	Coating Foundation	Minor repair work	80	2	160

2.5.4		Corrosion Protection **Passive**	Coating Tower	Minor repair work	80	6	480
2.6.0		**[6] Electrical Systems**			**80**	**3**	**240**
2.6.1			Lights	Lighting Inside	80	1	80
2.6.2				Lighting Outside	80	2	160
2.7.0		**[7] Other**			**80**	**22,5**	**1800**
2.7.1		Other	Safety Systems	Life saving equipment	80	0,5	40
2.7.2			Fire Fighting		80	2	160
			Extra		80	20	1600
					80		0
3.0.0	**[3] Subsea Installations**				**80**		**0**
					80		0
		Mooring Lines			80		0
		Anchors			80		0
		Cables			80		0
		In-service inspection	periodical inspection of sea cable.		80		0
4.0.0	**[4] 5th Year Major overhaul**				**80**	**220**	**17600**

Appendix B – Work Breakdown Structure

WBS	Component	TASK Name			Vessel		Weather Restriction	Duration in Hours	Comments/ Remarks
		Main Step	Sub steps	Action	No	Type		[h]	
1.0		**Transport and Installation**							
1.1.0		**Float out**						**10**	
1.1.1	Floating Wind Energy Production Unit (FWPU)	Float out & Towing preparation	Dry Dock flooded	Adjusting water levels and opening the gates				3	Duration is estimated, strongly depends on the dry-dock. Towed out at high tide with a draft of 6.7 m using three tugs [6].
1.1.2	FWPU	Float out & Towing preparation	Hook-up	Tugs entering the dock and connecting towing lines	3	Harbour Tugs (HT)	Tides/Wind	2	Estimate time, first attempts may take longer but a strong learning curve can be expected. Possible restricted to tides, depending on location and dock. Expert input from MH2
1.1.3	FWPU	Float out & Towing preparation	Float out		3	Harbour Tugs (HT)		2	Estimate, also dependent on the location, might be restricted (waiting for tides)
1.1.4	FWPU	Float out & Towing preparation	Ballasting	Pumping water into the platform ballast compartments, while the platform is held in place by three tugs. Removing the temporary buoyancy element	1/3	AHTS (Anchor handling tug supply vessel)/Harbour Tugs (HT)		2	Time is estimated; Source: Paper [6]
1.1.5	FWPU	Float out & Towing preparation	Preparation for Sea transport	Dis- & Reconnecting towing lines	1/3	AHTS (Anchor handling tug supply vessel)/Harbour Tugs (HT)		1	Exchanging 1 HAT with the OT, Could also be done after coastal water tow

1.1.6	FWPU	Float out & Towing preparation	Coastal Water tow	Towing the structure from the harbour area and crossing major shipping routes to the open sea	1/1	AHTS (Anchor handling tug supply vessel)/Harbour Tugs (HT)	Hs <2m		Assumption: 12nm + 3nm for inland waterways. Towing speed is 3nm/h
1.2.0		**Transit**						**2,5**	
1.2.2	FWPU	Tow-out	Transit to Wind farm		1	AHTS (Anchor handling tug supply vessel)/CTV	Hs <2m	0	From fabrication site to offshore location, towing speed 2-4nm/h, distance is project specific. 3nm/h is used in the calculation 2,5m Hs restriction from 20110315_WindFloat_Presentation_EWEA. Expert Input from MH2, 2,5m might be just for the transport itself. It is to optimistic considering MWS requirements. So 2m was chosen for the model.
1.2.3	FWPU	Tow-out	Transit in wind farm		1/2	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)	Hs <2m	1	Average transit time between two (2) locations or within the wind farm.
1.2.4	FWPU	Tow-out	Positioning of WindFloat	Running all DP checks and reaching final position	1/2	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)	Hs <2m	1	
1.2.5	FWPU	Tow-out	Turbine access	Deployment of Teams, Personal Transfer (PT) and tools on WTG via access system (e.g. Ampelmann),	1/2	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)	Hs <2m	0,5	Station keeping and personal access at the same time from the same vessel? Maybe with a FRB or Helicopter.

1.3.0		**Installation**						**13**	
1.3.1	Mooring	Hook-up and tensioning of mooring	Work preparation	Taking down sea fastening and set up of power supply	1/2/1	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)/ Fast Rescue Boat (FRB)	Hs<2m	1	From Paper 6, Restriction for access. Can be improved, Hs 2,5 m for X-Bow and Ampelmann set up. For nearshore locations PT can be performed with CTVs, in an Offshore location Teams have to be accommodated on the Platform or Construction Vessel (AHTSV) # Hook-up and tensioning of mooring requires 12hr weather window From 20110315_WF_presentation_EWEA
1.3.2	Mooring	Hook-up and tensioning of mooring	connecting messenger lines	Tug approaches WF and takes over ML from the foundation	1/2/1	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)/ Fast Rescue Boat (FRB)	Hs<2m	6	Assumed 1h per messenger line with a total number of 6 mooring lines. In the Demo project in Portugal only 4 mooring lines where installed [6]. Due to a conservative approach 6 mooring lines are assumed in this case
1.3.3	Mooring	Hook-up and tensioning of mooring	Pull in chain section	after connection messenger lines, chain section is pulled in	1/2/1	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)/ Fast Rescue Boat (FRB)	Hs<2m	3	Will be directly performed following the connection of the messenger wire, 1,5h per wire in total
1.3.4	Mooring	Hook-up and tensioning of mooring	Tensioning & Positioning of FWTG	Tensioned with the winch located on the platform and locked in chain-stoppers	1/2/1	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)/ Fast Rescue Boat (FRB)	Hs<2m	2	Estimate: Depends on team size and power supply [6]

1.3.5	Mooring	Hook-up and tensioning of mooring	Testing		1/2/2	AHTS (Anchor handling tug supply vessel)/Offshore Tug (OT)/ Fast Rescue Boat (FRB)	Hs<2m	1	
1.4.0		**Cable Installation**						**11**	
1.4.1	Cable	Cable Installation	preparation	Positioning of Cable Laying vessel (CLV)	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	0,5	Personal Transfer (PT) with a CTV/FRB (ampelmann is no option due to fact that shifts are not synchronised with vessel operations) , large effects on weather restrictions. Accommodation of teams is important (onshore vs. Offshore) but depends on the project
1.4.2	Cable	Cable Installation	preparation	Crew Transfer	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	1	Weather restriction is from a CTV, WR from the CLV and CTV could be different, most limiting WR has to be used.
1.4.3	Cable	Cable Installation	preparation	Work preparation	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	1	If heavy tools and equipment are needed 1h extra hour hast to be assigned for crane operations,
1.4.4	Cable	Cable Installation	Pull in	Cable inspection and Pick up of messenger line	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	1	
1.4.5	Cable	Cable Installation	Pull in	Pull in	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	5	
1.4.6	Cable	Cable Installation	Pull in	Installation "temporary hang off head"	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	0,5	

1.4.7	Cable	Cable Installation	Testing	OTDR and Isolation test	1/1	Cable Lay Vessel (CLV)/Crew Transfer Vessel(CTV)	Hs<1,5m	2	
1.5.0		**Termination**						**22,5**	
1.5.1	Cable	Termination		Crew Transfer	1	Crew Transfer Vessel (CTV)	H_S 1,5m	0,5	Main Limiting Condition is for Personal Transfer (PT). X-Bow and Ampelmann E-Type set up 2,5m, CTV 1,5-2m
1.5.2	Cable	Termination		Work preparation	1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	
1.5.3	Cable	Termination		Remove armouring, separating and cleaning of the individual conductors	1	Crew Transfer Vessel (CTV)	H_S 1,5m	5	
1.5.4	Cable	Termination		Attach power wires and fibre optic cable to cable tracks	1	Crew Transfer Vessel (CTV)	H_S 1,5m	4	
1.5.5	Cable	Termination	power connection	Connector assembly for 3 power wires and splicing the 24 optical cables	1	Crew Transfer Vessel (CTV)	H_S 1,5m	4	
1.5.6	Cable	Termination	power connection	Test preparation	1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	
1.5.7	Cable	Termination	Testing	Insulation test, OTDR measurement, VLF Test	1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	
1.5.8	Cable	Termination	Permanent Hang off		1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	
1.5.9	Cable	Termination		Clean up and disembarking	1	Crew Transfer Vessel (CTV)	H_S 1,5m	3	
1.6.0		**Commissioning**						**16**	
1.6.1	Floater Foundation	Commissioning	secondary trimming system		1	Crew Transfer Vessel (CTV)	H_S 1,5m	3	Main Limiting Condition is for Personal Transfer (PT). X-Bow and Ampelmann E-Type set up 2,5m, CTV 1,5-2m

1.6.3	Floater Foundation	Commissioning	Foundation Commissioning	Safety Systems and all others	1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	
1.6.4	Turbine	Commissioning	Remove Transport Lock		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	Depends On Turbine
1.6.5	Turbine	Commissioning	Commissioning WTG		1	Crew Transfer Vessel (CTV)	H_S 1,5m	3	Assumption: technical acceptance performed on land
1.6.6	Turbine	Commissioning	All systems		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	
1.6.7	Turbine	Commissioning	Testing		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	
1.6.8	Turbine	Commissioning	Clean up and disembarking		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	
		Planed operational Period T_{pop} critical							DNV_RP-H103 and DNV_RP-H101
		Net process time						**75**	

WBS	Component	TASK Name			Vessel		Weather Restriction	Duration in Hours	Comments/ Remarks
		Main Step	Sub steps	Action	No	Type		[h]	
2.0		**Tow In (Return to Onshore)**							
2.1.0		**Systems Shut down procedure**						**11**	
2.1.1	Floating Wind Energy Production Unit (FWPU)	Systems shut down procedure	Access	Crew transfer	1	Crew Transfer Vessel (CTV)	H_S 1,5m	0,5	Main Limiting Condition is for Personal Transfer (PT). X-Bow and Ampelmann E-Type set up 2,5m, CTV 1,5m
2.1.2	FWPU	Systems shut down procedure	WTG Shut Down		1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	Workload assumed
2.1.3	FWPU	Systems shut down procedure	Sea fastening	Transport lock and sea fastening preparation of WTG	1	Crew Transfer Vessel (CTV)	H_S 1,5m	3	Workload assumed
2.1.4	FWPU	Systems shut down procedure	WindFloat Shut Down	Putting WindFloat into transport mode	1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	Workload assumed
2.1.5	FWPU	Systems shut down procedure	Mooring system break off preparation		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	Workload assumed
2.1.6	FWPU	Systems shut down procedure	Reduce draft	Empty the operational ballast system	1	Crew Transfer Vessel (CTV)	H_S 1,5m	3	Workload assumed
2.1.7	FWPU	Systems shut down procedure	Prepare Back-Up power Supply		1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	Workload assumed
1.2.0		**Cable Disconnection**						**19,5**	
1.2.2	Cable	Cable Disconnection	Access of cable team	Crew transfer	1	Crew Transfer Vessel (CTV)	H_S 1,5m	0,5	

1.2.3	Cable	Cable Disconnection	Run back-up power generator	Switch from primary power supply to generator	1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	Workload assumed
1.2.4	Cable	Cable Disconnection	Shut down primary power supply		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	Workload assumed
1.2.5	Cable	Cable Disconnection	Disconnect power cable		1	Crew Transfer Vessel (CTV)	H_S 1,5m	4	Workload assumed
1.2.6	Cable	Cable Disconnection	Disconnect power fiber optic cable		1	Crew Transfer Vessel (CTV)	H_S 1,5m	1	Workload assumed
1.2.7	Cable	Cable Disconnection	Sealing cable		1	Crew Transfer Vessel (CTV)	H_S 1,5m	4	Workload assumed
1.2.8	Cable	Cable Disconnection	Installing cable pull head		1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	Workload assumed
1.2.9	Cable	Cable Disconnection	prepare winches and detach permanent hang off		1	Crew Transfer Vessel (CTV)	H_S 1,5m	3	Workload assumed
1.2.10	Cable	Cable Disconnection	detach cable	connecting messenger lines and lower cable	1	Crew Transfer Vessel (CTV)	H_S 1,5m	2	Workload assumed
1.2.11	Cable	Cable Disconnection			1	Crew Transfer Vessel (CTV)	H_S 1,5m		
1.3.0		**Disconnecting mooring system**						**7**	
1.3.1	Mooring	Disconnecting mooring system	Access		1	(CTV)	H_S 1,5m	0,5	
1.3.2	Mooring	Disconnecting mooring system	Work preparation		1	(CTV)	H_S 1,5m	1	Workload assumed

1.3.3	Mooring	Disconnecting mooring system	Connecting messenger lines		1	(CTV)	H_S 1,5m	2	Workload assumed
1.3.4	Mooring	Disconnecting mooring system	Hook-up	Connecting towing lines	1/1	AHTS (Anchor handling tug supply vessel)/CTV	Hs 2,0m	2	From offshore location to service, towing speed 2-4nm/h, distance is project specific. 3nm/h is used in the calculation 2,5m Hs restriction from 20110315_WindFloat_Presentation_EWEA. Expert Input from MH2, 2,5m might be just for the transport itself. It is to optimistic considering MWS requirements. So 2m was chosen for the model.
1.3.5	Mooring	Disconnecting mooring system	release chain section		1/2	AHTS (Anchor handling tug supply vessel)/CTV	Hs 2,0m	2	Workload assumed
1.3.6									
1.4.0		**Tow In**						**7**	
1.4.1	FWPU	Tow in	Transit in wind farm		1/2	(AHTS)/ Offshore Tug (OT)	Hs 2,0m	1	From offshore location to service, towing speed 2-4nm/h, distance is project specific. 3nm/h is used in the calculation. Depending on the Wind farm layout it might be necessary to manoeuvre the FWPU- so more then only the AHTS
1.4.2		Tow in	Transit to onshore service hub		1	AHTS	Hs 2,0m	0	From the offshore location back to shore, towing speed 2-4nm/h, distance is project specific. 3nm/h is used in the calculation
1.4.3		Tow in	Positioning of WindFloat in the dry dock		3	Harbour Tugs (HT)		6	Assumed to be similar to float out time
1.5.0								**0**	
1.6.0								**0**	
		Planed operational Period T_{pop} **critical**							
		Net process time						**44,5**	