Reference O&M Concepts for Near and Far Offshore Wind Farms

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December 2016
ECN-E—16-055

Acknowledgement

This report is written within "Offshore Maintenance Joint Industry Project (OM JIP)", partially funded by TKI Wind op Zee. This project is cooperation between ECN, MARIN, TNO, BMO Offshore, Carbon Trust and Dutch industry participants.

Abstract

Offshore wind farm Operation and Maintenance ("O&M") costs are a major part of levelised cost of energy, and significant opportunities exist for improving O&M strategies to reduce costs. A major contributor to high O&M costs is downtime caused by accessibility restrictions, as severe weather conditions offshore restrict times for technician transfer to the wind turbine platforms or completion of maintenance tasks. Existing accessibility models consider very few metocean parameters (mainly wind speed and significant wave height) for limiting accessibility. In reality, offshore wind accessibility is much more complex, and improved understanding will lead to improved use of vessels and weather windows, thereby reducing O&M costs and improving availability.

Within the OM JIP project new datasets and techniques for understanding accessibility are being created and then incorporated in an updated version of ECN's modelling tool. Metocean data are first translated to vessel hydrodynamics, then vessel motions are translated to human fatigue and workability.

This report defines five reference offshore wind farms, representing current and future wind farms. The existing accessibility model is then applied to calculate costs and downtimes for an optimal O&M concept for each wind farm. Total costs range from 35.3 M€/year for a nearshore, 20m deep Dutch wind farm, to 84.3 M€/year for a far offshore, 30m deep UK wind farm. Savings associated with choosing optimal equipment or strategies are calculated and presented for each wind farm scenario.

Keywords: offshore wind, Operation and Maintenance (O&M), crew transfer vessels, service operation vessels, harbor based strategy, offshore based strategy, hybrid strategies, key performance indicators.

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Summary

Offshore wind operation and maintenance costs are a major part (20-30%) of the Levelised Cost of Energy (LCOE), which can be reduced significantly by implementing an optimal O&M strategy. A major contributor to high O&M costs is downtime caused by accessibility restrictions, as severe weather conditions offshore restrict times for technician transfer to the wind turbine platforms or completion of maintenance tasks.

Existing accessibility models consider very few metocean parameters (mainly wind speed and significant wave height) for limiting accessibility, while in reality offshore wind farm accessibility is much more complex. Within the OM JIP project a new accessibility model is defined, where metocean data are first translated to vessel hydrodynamics and then, vessel motion is translated to human fatigue and workability. In order to demonstrate the added value of this model, O&M costs and downtimes are calculated using both models: the existing simple accessibility model; and the improved one developed within the OM JIP project. To do so, five reference wind farms (**Figure 1**) representing current and future near shore and far offshore farms are now defined.

Figure 1: Five reference wind farms selected for O&M Case study

Several O&M concepts based on harbour based, offshore based and hybrid based strategies for each wind farm are described in this report. Moreover, specific case studies for each of the wind farm are performed, choosing a suitable O&M concept. Substantial cost savings are made by smart choices while choosing a certain O&M strategy for a wind farm. For Wind Farm A (100 turbines, 30 km from shore), adding a ladder access system to the CTV resulted in **3 M€/year** of cost reduction. Similarly, for another wind farm (Wind Farm B: 50 turbines, 30 km from shore), including helicopter as the secondary equipment leads to a cost saving of **0.5 M€/year**. Hybrid strategies (sharing harbour, resources, etc. between two different wind farms) are also explored as part of this report. Employing such a strategy for two similar wind farms (Wind Farm B1-B2) as compared to operating a single wind farm individually ensued a total saving of **6.7 M€/year.** Likewise, considering a hybrid strategy by sharing Service operating vessels (SOV) and permanent bases for far-offshore wind farms (Wind Farm C, D: 800 MW, 150 km from shore), a total reduction in tune of **28.5 M€/year** is feasible.

Specifically, for each wind farm, a suitable case study is discussed in detail. **Table 1** summarizes the results for *five* offshore wind farms as part of the case studies.

Table 1: Summary of *five* Case Studies- Wind Farm Specs, O&M Strategy and Output KPI's

Wind Farm	Wind Farm Specs	O&M Strategy	Availability (% Time, % Yield)	Costs per kWh[1]	Total Costs (O&M, Revenue loss)
A	400 MW (100*4 MW), 30 km from Danish coast, 20 m deep	CTV + access gangway	94.6%, 94.3%	2.33 c€/kWh	**41.2 M€/yr**
B	400 MW (50*8 MW), 30 km from Dutch coast , 20 m deep	CTV + helicopter	94.8%, 94.6%	1.53 c€/kWh	**35.3M€/yr**
		Hybrid (shared harbour & resources)	94.8%, 94.5%	1.09 c€/kWh	**57.2M€/yr**[2]
C	800MW (200*4 MW), 150 km from UK coast, 30 m deep	Offshore permanent base	93.6%, 93.0%	1.86 c€/kWh	**84.3 M€/yr**
D	800 MW (100*8 MW), 150 km from German coast, 50 m deep	Offshore Floating base (SOV)	94.5%, 94.3%	1.39 c€/kWh	**75.2 M€/yr**
E[3]	400 MW (50*8 MW), 20 km from Norwegian coast, 200 m deep	SOV + towing vessel	91.4%, 90.4%	2.82 c€/kWh	**62.2 M€/yr**

O&M modelling is of significant importance for the developer, both during the planning phase and actual operation. Within this study, it is shown that the O&M modelling can help support users in technology selection (type of turbine, access systems, service vessels and equipment), LCOE calculations, long term O&M planning, short term and end of lifetime decisions, etc. Furthermore, under OM JIP, ECN O&M Access will be developed further, where vessel hydrodynamics and human fatigue will be included to better evaluate the actual performance and effort during Operation and Maintenance.

[1] The price of energy assumed for the *five* case studies is 13 c€/kWh

[2] The total revenue cost represents the overall effort for two wind farms of 400 MW each, as following hybrid strategy, the resources are shared between both. For a single wind farm representative of site B, the overall costs will be half of it (28.63 M€/yr).

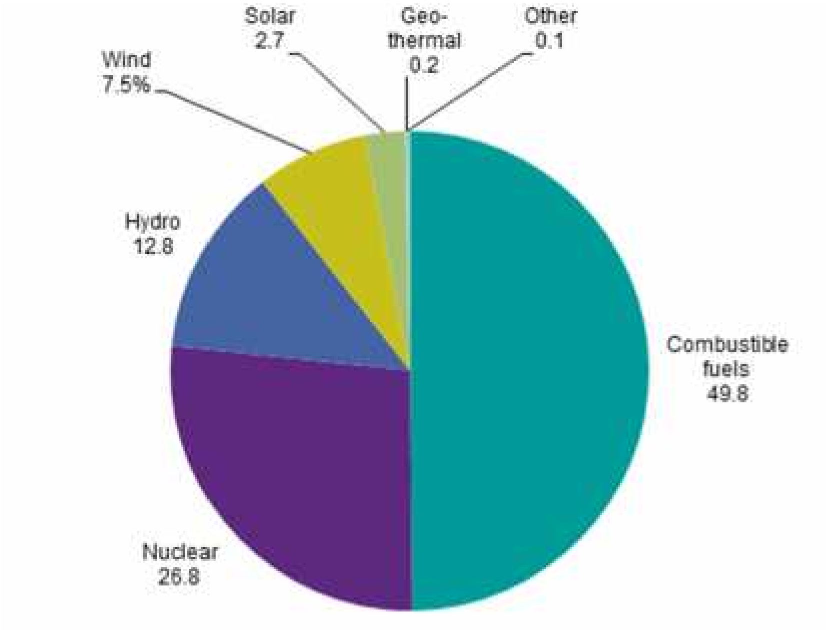
[3] Floating offshore wind farm

1

Introduction

As illustrated in **Figure 2**, about 50% of the net 3100 TWh electricity generation of EU-28 in 2013 was through fossil fuels. This number goes to 75% considering all non-sustainable energy sources, both fossil fuels and nuclear power plants. In recent years, European countries are actively supporting electricity generation from renewable sources, such as wind power plants. In addition to the governmental and European supports and subsidies, renewable sources should be economically feasible, which requires innovative solutions to bring their development and operation costs down.

Figure 2: Net electricity generation of EU-28 in 2013 [31]

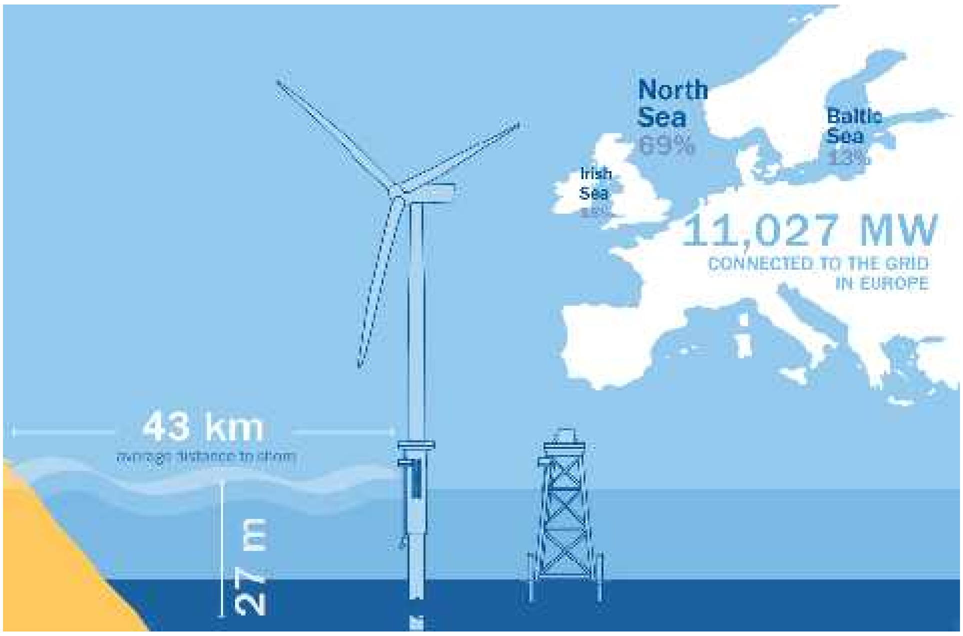


This report gives an overview of future European offshore wind farm types in the North Sea and then, estimates their yearly operational costs based on traditional and innovative maintenance strategies. Furthermore, a new joint industry project is introduced where European industries and knowledge institutes are joining forces to more accurately estimate offshore wind operational costs.

1.1 Offshore Wind Energy

As shown in **Figure 3**, by the end of 2015 more than 3000 offshore wind turbines were installed in Europe making a cumulative installed capacity of 11 GW [29][28]. The average size of an European offshore wind farm is 338 MW, where on average they are located 43 km far from the shore and in 27 m water depth.

Figure 3: European offshore wind energy statistics 2015 [28]

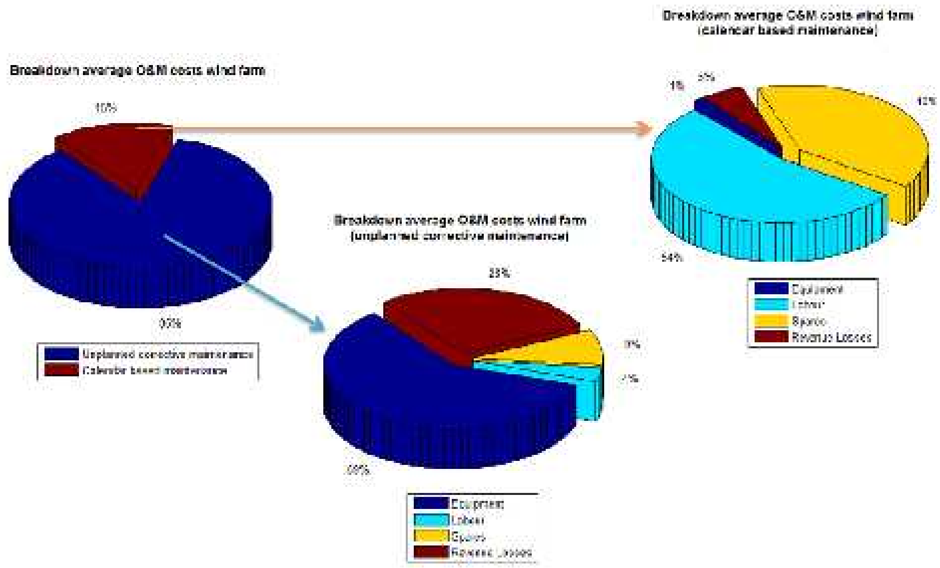


As seen the figure above, the majority of the European offshore wind farms are located in the North Sea region and for that reason, the five reference wind farms presented in the following chapter are all located in this region. Looking at coming European offshore wind tenders it can be seen that there are several tenders for near shore, far offshore and floating offshore wind farms. Therefore, in this report all three offshore wind farm type are considered.

1.2 Operation & Maintenance

The operation and maintenance costs account for 25% of the life cycle costs of offshore wind farms, where the majority of costs are associated with unplanned corrective maintenance actions. As shown in **Figure 4** the unplanned maintenance costs are contributing to 90% of total O&M costs, where 28% of that is due to the weather downtime and revenue losses.

Figure 4: Breakdown of yearly maintenance costs based on the reference wind farm of ECN O&M Access V1.0 (more explanation on ECN O&M modelling discussed in Section 1.3).



It is shown in several studies such as [29] that updating the maintenance strategy can reduce approximately 10% of operational costs. In an optimal maintenance strategy the right selection of access vessels and access gangways can be used to facilitate the transfer of technicians to the turbines throughout the year and reduce long waiting times in the winter season.

1.3 ECN O&M Modelling

ECN is a market leader and developer and owner of the industry standard O&M strategy modelling tools designed especially for offshore wind, validated by GL and in use for nearly fifteen years. ECN provides consultancy and licenses and has a customer base (O&M) of more than 30 of the industry's leading companies. These are nearly all the developers and wind turbine manufacturers active in the offshore wind sector.

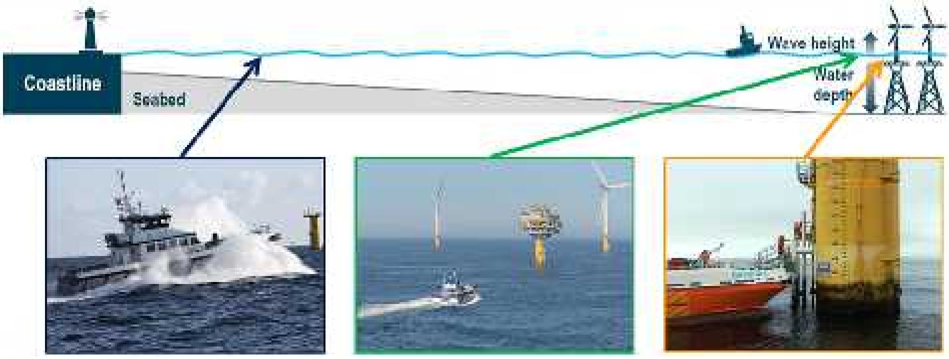
With these tools, ECN has recently provided consultancy support in O&M strategy modelling for various developers (in application for the tender) for the Borssele offshore wind tenders. ECN was chosen for this work not only for its leading models but also its extensive experience and expertise in real failure frequencies of wind farm components and the metocean conditions in the Dutch part of the North Sea.

For this study, "ECN O&M Access" tool is used to model different O&M strategies and calculate the corresponding effort both in time and cost.

1.4 Offshore Maintenance JIP

The Offshore Maintenance Joint Industry Project (OM JIP) is a project initiated by ECN, MARIN, TNO and in cooperation with CarbonTrust, BMO Offshore, NLR, Ampelmann, Damen, SeaSpead, StormGeo, Vroon, Sky-Access and ActaMarine. This project is focused on improved accessibility models for maintenance of offshore wind farms where vessel hydrodynamics and human fatigue are introduced.

Figure 5: Demonstration of transit, approach and transfer phases for offshore wind access vessels [MARIN]

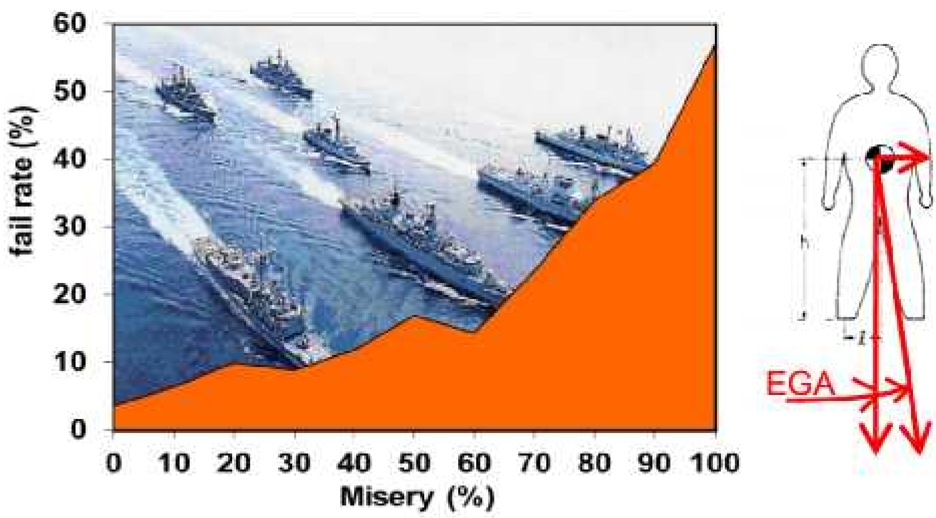


As illustrated in **Figure 5** in this project access vessels during transit, approach and transfer phases are modelled. The execution of the project is in three steps:

1. Translation of sea state data into vessel hydrodynamics during transit, approach and transfer phases. This hydrodynamics database is prepared for five selected access vessels, three crew transfer vessels (CTVs) and two service operation vessels (SOVs). The CTVs are approximately 20m long monohull, catamaran and swath types. The SOVs are 60m and 84m long monohull vessels.

2. Translation of vessel hydrodynamics into human fatigue and operability. In this part seasickness, postural stability, motion induced fatigue, sleepiness and motion induced interruption are considered. In **Figure 6** results of a NATO trial are shown where the relation between the seasickness (misery) and performance (fail rate) is demonstrated.

Figure 6: NATO trial on human fatigue and seasickness [TNO]



3. Translation of human operability into total O&M costs, where ECN is further developing the accessibility model of the O&M Access V1.0 model using the results of this project.

The updated version of the ECN O&M Access tool will be based on human fatigue and vessel hydrodynamics for five selected access vessels. Moreover, five reference offshore wind farm will be also included in the tool representing the typical European offshore wind farms in the North Sea. In the next chapters, more detail on these wind farms (Chapter 2) and their modelled maintenance strategies (Chapter 4 & 5) is provided.

2

Reference Wind Farms

Offshore wind farm development is primarily flourishing in Western European countries. Although, there is a promising market in South Asian countries including China, Japan, Korea and Taiwan; the reference wind farms selected in this study are sites in the North Sea of European waters. However, they do represent the characteristics of the upcoming market in Asia and US. In all, *five* wind farm sites are considered for this study. These sites are also differentiated based on the colour map of the wind potential and the water depths in the North Sea. These maps are shown in the **Figure 7** and **Figure 8** respectively.

Figure 7: Colour Map- Wind potential of the North Sea [1]

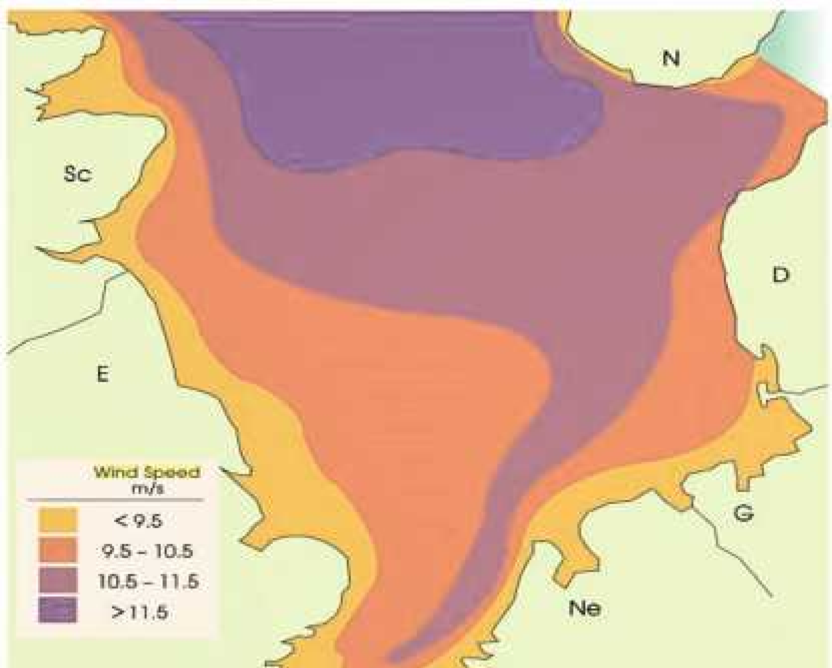
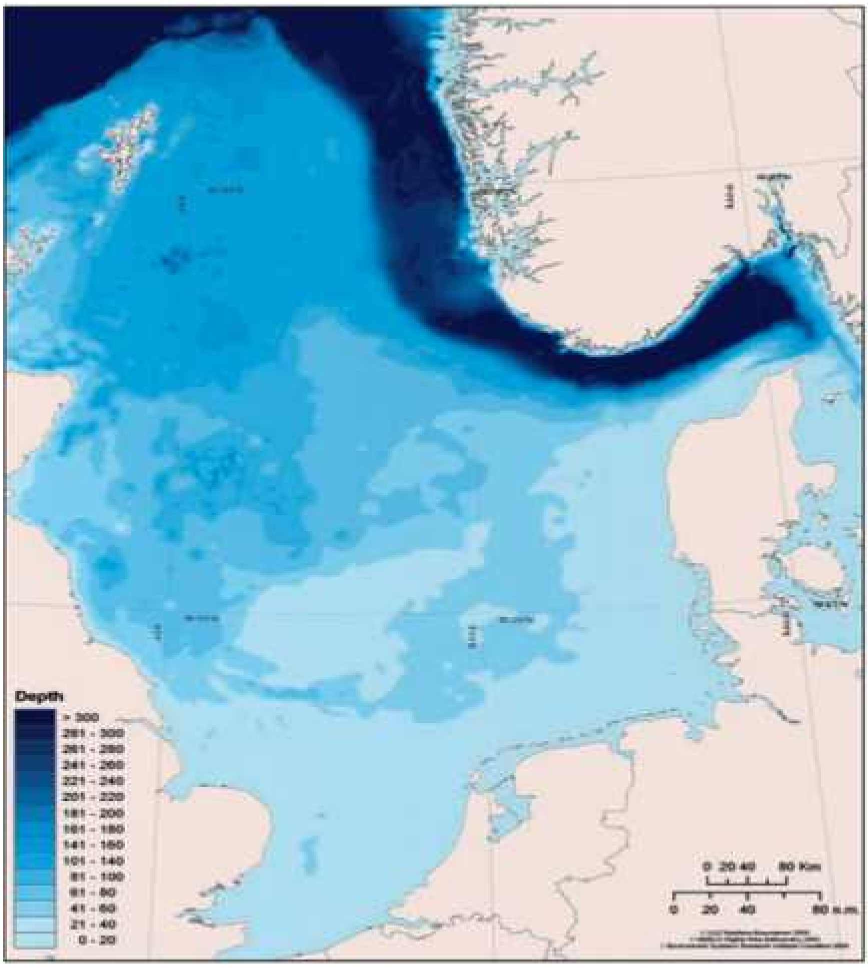


Figure 8: Colour Map- Water Depth of North Sea [1]



Specifically, from **Figure 8**, it is clear that the North Sea may be divided into *three* regions. These are:

(a) Southern Bight (51-54°N) with water depths of less than 40m;

(b) Central North Sea (54-57°N) with water depths of 40-100m except for the shallower areas on the Dogger Bank and along the western coastline of Denmark and;

(c) Northern North Sea (north of 57°N) including an area of shelf water 100- 200m deep, and the Norwegian Channel with water depths from 200 to >700m in the Skagerrak between Denmark and Norway [1].

Moreover, for the selection of wind farms sites, a definite effort is made to include both the wind farms under development and planned future wind farms (till the period 2020).

Sections 2.1 to 2.5 of this report elaborate on the different wind farms selected. Section 2.6 summarize and depicts a pictorial representation of the different wind farm sites chosen.

2.1 Wind Farm A

Most of the wind farms which were built in the last two years had an average capacity of around 300-400 MW [28]. Moreover, due to popularity of 4.0-6.0 MW turbines, the average turbine size in 2015 was 4.2 MW [2]. The industry has slowly matured to this combination of 400 MW wind farm size and 4 MW wind turbine size. Moreover, as indicated in the introduction to this chapter, the said combination is considered to account for the already existing and few planned offshore wind farm sites. The exact characteristics of such a wind farm is tabulated in **Table 2**. Some of the example wind farms which lie in this category are Sheringham Shoal wind farm in UK (existing), Horns Rev 3 offshore wind farm in Denmark (planned).

Table 2: Characteristics of Wind Farm A

Parameters	Values
Capacity of wind farm (MW)	400
Number of Turbines	100
Turbine Size (MW)	4
Distance from harbor (km)	30
Water Depth (m)	20

2.2 Wind Farm B

The wind farm industry is gradually progressing into the phase where wind turbine size of 6MW/7MW/8MW are being readily accepted. The wind farm developers and investors are finalizing the large machines for their future wind farm sites. Leading manufacturers like Siemens, Vestas, Adwen, etc. are already having commercial solutions for upcoming wind farms in Europe and Asia. So, as an alternate to the above case of Wind Farm A, the option of larger machines is considered for this case. All the other parameters including capacity of wind farm, water depth and distance are considered as same. The final numbers are documented in **Table 3**. Moreover, some of the example sites which could consider this combination is the upcoming Borssele wind farm area development zone in the Netherlands [4] and the Horns Rev 3 in Denmark [3]

Table 3: Characteristics of Wind Farm B

Parameters	Values
Capacity of wind farm (MW)	400
Number of Turbines	50
Turbine Size (MW)	8
Distance from harbor (km)	30
Water Depth (m)	20

2.3 Wind Farm C

In the introduction of the Chapter, it was discussed that there is a Central zone of the North Sea which is of primary interest to the wind farm developers. Although the site location is far-off from the coast, the water depth in some of the locations (Dogger Bank area) is not that deep [1]. Also, it makes more sense to consider large offshore wind farms for these sites. Hence, a combination of large distance from shore (150 m), average water depths (30 m) and huge wind farm (800 MW) is categorized as Wind Farm C. The exact parameters are shortlisted in **Table 4**.

Table 4: Characteristics of Wind Farm C

Parameters	Values
Capacity of wind farm (MW)	800
Number of Turbines	200
Turbine Size (MW)	4
Distance from harbor (km)	150
Water Depth (m)	30

2.4 Wind Farm D

In section 2.3, a wind farm site location of a distance of 150 km is considered. An alternate situation could be the part of North Sea where the distance from shore is similar as in case of Wind Farm C, but the water depths are higher; that in the range of 50 m. Moreover, the sites are deep enough to opt for Jackets as compared to Monopiles for foundation structure. Another difference considered in this case is the size of the wind turbine. 8 MW machines are used as compared to 4 MW in the Wind Farm C. Finally, the combination of the Wind Farm D is tabulated in **Table 5**. Future offshore wind farm development in Germany [5] and UK [6] are in this type of range.

Table 5: Characteristics of Wind Farm D

Parameters	Values
Capacity of wind farm (MW)	800
Number of Turbines	100
Turbine Size (MW)	8
Distance from harbor (km)	150
Water Depth (m)	50

2.5 Wind Farm E

In addition to the fixed machines, there is a growing interest in the floating offshore machines. Prototypes like Hywind (in Norway), Wind Float (in Portugal) and that in Japan (off the Fukushima coast) are successful examples of the technology [7]. Moreover, to cover the future wind farm locations including the Northern North Sea (Norwegian Channel) and South East Asia, a floating wind farm is selected. The wind farm is more or less similar to Wind Farm B in terms of capacity, number of turbines and turbine size. The distance to the shore is marginally close and the water depths are really deep. The final values are documented in **Table 6**.

Table 6: Characteristics of Wind Farm E

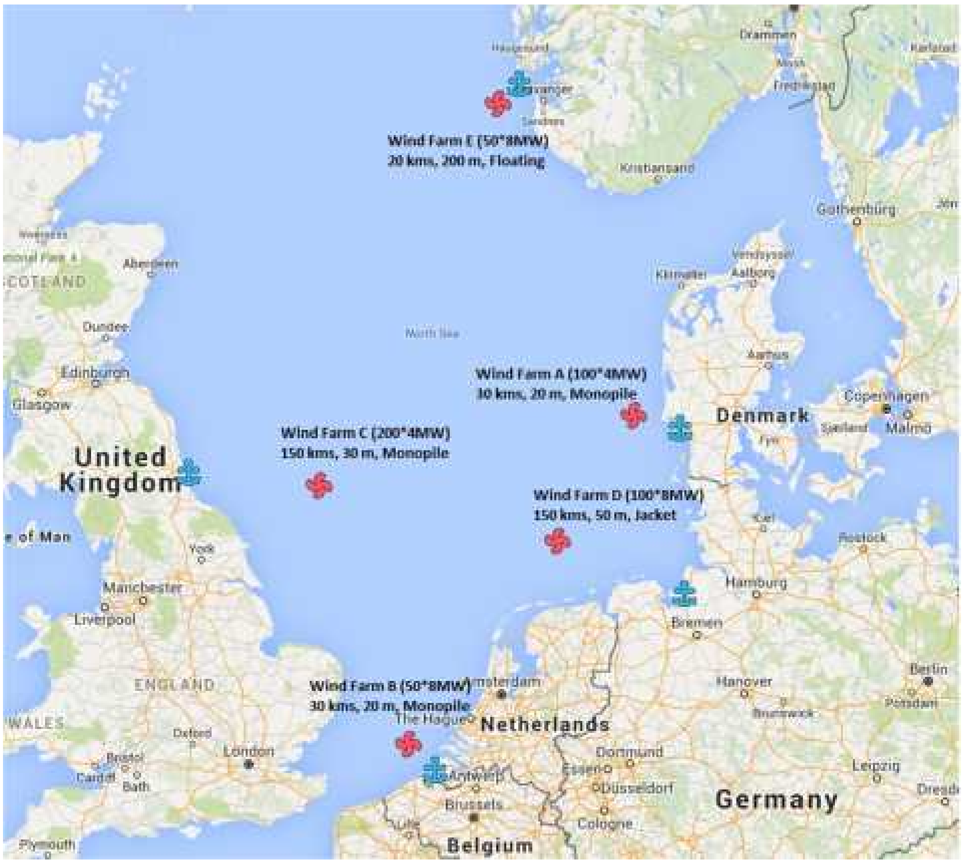
Parameters	Values
Capacity of wind farm (MW)	400
Number of Turbines	50
Turbine Size (MW)	8
Distance from harbor (km)	20
Water Depth (m)	200

2.6 Summary

The study in this report combines two aspects- viz. (a) Existing and future wind farm locations; (b) Existing and future O&M strategies. This chapter summarizes the different wind farm location sites selected for this study. A sincere effort is made to include the future wind farm developments in Europe (North Sea, Baltic Sea) and Asia (South-East). Moreover, to account for the actual weather conditions at these sites, actual satellite weather data representative of these locations have been considered.

The different locations selected are marked in **Figure 9**. The red fan markers are representative of the wind farm locations and the blue locks that of harbours for the corresponding find farm. Specifically, countries like UK, Denmark, Germany, Netherlands and Norway are chosen to indicate the progressive offshore wind farm markets in Europe.

Figure 9: Selected Wind Farm locations in North Sea (Google Maps)



In the next chapter, corresponding to each wind farm locations, different operation and maintenance strategies are chosen and described. The following Chapter evaluates these maintenance strategies in terms of availability and cost for the chosen wind farm site locations.

3

O&M Equipment

At the heart of all O&M lies the equipment with which the technicians access the wind farm and repair the turbines. The equipment can be anything from transfer vessels to cranes to access systems, etc. Further, to access the wind turbine there are different ways [18]:
(i) Direct boat landing, from where the technicians climb the ladder to reach at the platform;
(ii) The platform, where technicians can enter directly the tower;
(iii) The helideck, which provides direct access to the Nacelle.

The different access vessels and systems are discussed in the sections below. It is noted that only selected O&M Equipment specific to this report are discussed.

3.1 Crew Transfer Vessels (CTVs)

CTV's are the most commonly used way of accessing offshore wind turbines. The technicians access the later by boat landing, on the structure's ladder. It is a cost-effective and fast solution. However, due to safety implications and offshore wind farms being installed farther from shore, there has been research into better and larger crew transfer vessels as well. There are different types of CTV's, namely:

(a) Rigid Inflatable Boats (RIBs) or Daughter Crafts;
(b) Workboats or Catamarans;
(c) SWATH vessels.

The choice of the CTV is based on the capacity of technicians or spare parts required, the distance of the wind farm from shore and the operability of the CTV.

A Catamaran is characterized by the two parallel hulls; they have a deck suspended between them. The deck contains the bridge and accommodation module. They are characterized by good seafaring capabilities until the weather becomes extremely severe. They travel at high speeds and have a small water plane area, which can be a huge advantage when traveling. Their disadvantage is that they become uncomfortable in beam seas when the weather deteriorates. Furthermore, catamarans cannot carry any significant payload unless the vessel is rather large [9]. **Figure 10** shows the example workboats which are used for such medium sized wind farm (e.g. Wind Farm A discussed in Section 2.1). Moreover, **Table 7** summarizes the technical and the cost specification of such a CTV. The logistic data highlights the operational technical capabilities of the equipment and the cost and availability data states the equipment count available for different maitnenance type and corresponding leasing charges. It should be noted that the number of equipment available is an assumption and it will be used for all the case studies documented in Chapter 5.

Figure 10: Example of Catamaran access vessels: the Wind Cat MK [10] on the left and the CTruk [11] on the right

Table 7: Equipment Logistic & Cost-Availability specification for a small CTV

Equipment Name	Logistic Data		Cost & Availability Data	
CTV-S (small)	Speed	20 knots.	Number of Equipment available (shared[4])	3
	Travel Weather Limit (Hs max, Vw max)	1.5 m, 12 m/s	Cost of the Equipment (shared)	€ 350K/yr + € 100/trip
	Transfer Weather Limit (Hs max, Vw max)	1.5 m, 12 m/s	Number of Equipment available (condition)	3
	Maximum Technicians	12	Cost of the Equipment (condition)	€ 1500/day + € 100/trip

The CTV's discussed above limit the maintenance operations in terms of accessibility and the capacity of technicians and spare parts. The later reason is more critical and requires the use of bigger catamaran or SWATH workboats inevitable. The bigger wind turbines have heavier spare parts size and a complementary large capacity tower and nacelle crane. Some of the workboats which are presribed for such wind farms (Wind

[4] Shared between Corrective and Calendar based maintenance.

Farm B) are shown in **Figure 11**. Also, **Table 8** summarizes the logistic capabilities and the cost overview of such large CTV's. It should be noted that the sole reason of using bigger CTV's is the capability to load and transfer heavier spare parts for bigger 8MW turbines. Addtionally, it brings an added value of its feasible operations in tougher weather conditions.

Figure 11 Example of large sized workboat access vessels: the CWind [12]and Alicat South Boats from Seacat Services [13]on the right.

These workboats not only have higher capacity and workability, but also have higher speeds of travelling. Since the travelling time is also counted as the working time [9], for far-offshore wind farms, the actual working window on wind turbine is less. Such workboats facilitates safe and fast transfer of crew and small spare parts.

Table 8: Equipment Logistic & Cost-Availability specification for a large CTV

Equipment Name	Logistic Data		Cost & Availability Data	
CTV- XL (large)	Speed	25 knots	Number of Equipment available (shared)	3
	Travel Weather Limit (Hs max, Vw max)	2.0 m, 15 m/s	Cost of the Equipment (shared)	€ 500K/yr + € 500/trip
	Transfer Weather Limit (Hs max, Vw max)	2.0 m, 15 m/s	Number of Equipment available (condition)	3
	Maximum Technicians	12	Cost of the Equipment (condition)	€ 2250/day + € 500/trip

3.2 Access Systems

The regular vessels are a major part of transporting O&M crews to and from the offshore turbines. However, the subject of high accessibility and contract agreement between the turbine operators and owners of the wind farm to achieve certain availability levels has gradually made the offshore wind industry to choose for transfer systems. Hence, it is not only necessary to select the best suitable vessel for the wind farm, but also of paramount importance to combine the vessel with a suitable means of transfer. These access systems enable safe transfer of crew personnels and sometimes spare parts. Further, it should be noted that based on the vessel chosen for wind farm O&M (shore based O&M approach), the size and weight of the transfer system also differ.

The application of access system is not limited for the wind farms far from shore. It can be used for smaller and near shore wind farms until there is a technical requirement (workability) and the economics of O&M vs. Availability of the wind farm allows the operator to incorporate such systems. Moreover, these transfer systems or access systems are expensive equipments [9]. There are mainly two types of access systems: (a) CTV Enhancement systems; (b) Platform Access systems [18].

The first type is mainly a gangway which is used for improving the accessibility and safety performance of the O&M operation. These systems can either be mounted on the foredeck compensating vessel's motions or on the turbine's structure, both assisting access to the turbine's ladder. The requirements for the vessel characteristics (e.g. length) and boat landing vary for each systems as well as the compensation method (active or passive). Some of the commercial solutions available in form of gangways are shown in **Figure 12**. The summary of the logistic and cost overview after the addition of such an access gangway is tabulated in **Table 9**.

Figure 12: Commercially available access gangways for enhancing CTV's performance. Ampelmann L-Type [19], Autobrow [20]and BMT & Houlder TAS [21].

Table 9: Equipment Logistic & Cost-Availability specification for a small/large CTV with an access gangway

Equipment Name	Logistic Data		Cost & Availability Data	
CTV-S + gangway	Speed	20 knots	Number of Equipment available (shared)	3
	Travel Weather Limit (Hs max, Vw max)	2.0 m, 12 m/s	Cost of the Equipment (shared)	€ 600K/yr + € 100/trip
	Transfer Weather	2.0 m,	Number of Equipment	3

	Limit (Hs max, Vw max)	12 m/s	available (condition)	
	Maximum Technicians	12	Cost of the Equipment (condition)	€ 1500/day + € 100/trip
CTV- XL + gangway	Speed	25 knots	Number of Equipment available (shared)	3
	Travel Weather Limit (Hs max, Vw max)	2.5 m, 15 m/s	Cost of the Equipment (shared)	€ 750K/yr + € 500/trip
	Transfer Weather Limit (Hs max, Vw max)	2.5 m, 15 m/s	Number of Equipment available (condition)	3
	Maximum Technicians	12	Cost of the Equipment (condition)	€ 2250/day + € 500/trip

The second type of access systems provide direct access to the platform. These gangways are mostly motion compensated and provide direct access of personnel to the platform in a safe manner by eliminating the vessel motions. Most of the motion compensation gangways require a Dynamic Positioning (DP) vessel of certain size (usually longer than 50 m) and depending on their cargo capacity, they can also be used for equipment and/or spare parts. These gangways are mostly incorporated with the larger Mother vessels (discussed in Section 3.4) or Service Operation Vessels (SOVs) which are usually equipped with an additional crane for lifting operations. Some of the commercial available access systems for such gangways are shown in **Figure 13**. Offshore Access System (OAS) is normally employed for longer operations and requires a DP 2 vessel [15]. These access systems have capability of transfering crew at significant wave heights (H_s) of 2.5-3.5 m.

Figure 13: Commercially available access systems. Ampelmann A Type [14]on the left and Offshore Access System (OAS) [15]on the right.

Furthermore, a detailed overview and summary of the capabilities of the different access systems can be referred to in the ECN report- Access for Offshore Wind Operations and Maintenance [18].

3.3 Helicopters

An alternative O&M methodology used for existing wind farms is the use of helicopter. Again, if the weather accessibility is low and there is a rather urgent requirement of crew transfer, use of helicopters might be a viable option. The added value of helicopters is of course because of its least dependency on the wave and current climate. This improves the accessibility to the wind farm by a great margin. Additionally, the maintenance trips are significantly shorter. To state a comparison, it shall take a catamaran workboat up to six hours to reach the giant Dogger Bank wind site in the North Sea, and that is with significant wave heights of less than 1.5 m or wind speeds less than 10 m/s. A helicopter does it in 25 minutes [17].

However, there is always a debate on the feasibility and safety of the transfer operations through helicopter. Moreover, according to the trends, majority of projects above 300 MW are featuring either a helideck or heli-hoist platform on the associated offshore sub-stations [16]. This implies that technical and economic feasibility of helicopters is based on (a) Weather conditions at the wind farm location; (b) Size of the wind farms; (c) Distance of the wind farm from shore. Currently, helicopters are in regular use for turbine O&M purposes at the Horns Rev Project in Denmark, Alpha Ventus, Global Tech 1 and Borkum Phase 1 (when commissioned). **Figure 14** shows the helicopter access in Alpha Ventus wind farm. As an operator, an interesting strategy could be to employ helicopter as a stand-by transfer system and use workboats for the daily operation. Additionally, the overview of logistic and cost specifications are summarized in **Table 10**.

Figure 14: Offshore wind helicopter access at Alpha Ventus [22]

Table 10: Equipment Logistic & Cost-Availability specification for a Helicopter

Equipment Name	Logistic Data		Cost & Availability Data	
Helicopter	Speed	120 km/hr	Number of Equipment available (corrective)	1
	Travel Weather Limit (Hs max, Vw max)	99 m, 20 m/s	Cost of the Equipment (corrective)	€ 6000/day
	Transfer Weather Limit (Hs max, Vw max)	99 m, 20 m/s		
	Maximum Technicians	6		

3.4 Mother Vessels or SOV's

The offshore wind farms are being installed and commissioned further from the shore. The mother vessels, also referred to as SOV (Service Offshore Vessel) are a part of the new O&M strategy that the offshore wind industry is considering for far-offshore wind farms. These SOV's enable the technicians to remain offshore without going back and forth from the shore base with additional CTV's on board. The main purpose, therefore is to host technicians, spare parts and repair facilities for a longer time offshore, allowing O&M tasks to be more efficiently conducted and avoiding longer transfer time.

Some of the commercial solutions available for these types of SOV's are illustrated in **Figure 15**. These SOV's possess an access gangway for personal and spare parts transfer. The helipad is optional and depends on the end requirements of the owner of the wind farm. In general, it can house somewhere from 40 to 60 technicians and 2-3 CTV's or daughter crafts on board. Commercially, these vessels are now being under serious consideration and some existing offshore wind farms like Baltic 2, Butendiek and future wind farms like Dudgeon [23] have already included them in their daily O&M operations. Specifications for these SOV's are summarized in **Table 11**. It should be noted that the SOV is normally situated offshore, hence the only travelling time considered is that of "within the wind farm".

Table 11: Equipment Logistic & Cost-Availability specification for a Mother vessel or SOV

Equipment Name	Logistic Data		Cost & Availability Data	
Mother Vessel or SOV	Speed	10 knots	Number of Equipment available (shared)	1
	Travel Weather Limit (Hs max, Vw max)	3.0 m, 17 m/s	Cost of the Equipment (shared)	€ 12M/yr + € 100/trip

	Transfer Weather Limit (Hs max, Vw max)	3.0 m, 17 m/s	Number of Equipment available (condition)	1
	Maximum Technicians	60	Cost of the Equipment (condition)	€ 2250/day + € 100/trip

Under this report, for far-offshore wind farms, such SOV's are included in the maintenance strategy to evaluate the added value. Wind Farm C or D mentioned in Section 2.3 and 2.4 are the most suitable selections.

Figure 15: Commercial examples of SOV's or Mother Vessels. ESVAGT [23]on the left and Damen Walk to Work [24]on the right.

3.5 Towing Vessels

During the operational years of offshore wind industry, different wind turbine components have been towed to the wind farm location offshore. Based on the size of the component, a suitable vessel is chosen. For e.g. in Gemini wind farm installation, the offshore sub-station was towed on a jack-up barge and pulled by tug-boats. Additionally, all the currently installed floating offshore wind turbines have also been installed by floating through the tug-boats. Although, the examples mentioned are only for the installation of floating turbines. Maintaining floating turbines offshore is a rather complex operation, especially if it requires a replacement of a part of the turbine. Hence, different solution from a normal tug boat to more innovative solution can be used. They are illustrated in **Figure 16**. Note that these illustrated pictures just show the installation of offshore wind turbines. However, they can be applied for replacement as well. **Table 12** summarizes the logistic and cost specifications of a towing vessel considered for the case study. The towing vessel is only used in the case of maintaining floating offshore turbines.

Figure 16: Solutions for towing the turbine back onshore. Using Tug boats on the left and innovative concept of Ulstein

Table 12: Equipment Logistic & Cost-Availability specification for a Towing vessel

Equipment Name	Logistic Data		Cost & Availability Data	
Towing vessel	Travel Time	8-10 knots	Number of Equipment available (corrective)	1
	Mobilization Time	72 hrs	Cost of the Equipment (corrective)	€ 20K/hr + € 300K/Mob or Demob
	Demobilization Time	72 hrs		
	Travel Weather Limit (Hs max, Vw max)	1.5 m, 12 m/s		
	Transfer Weather Limit (Hs max, Vw max)	1.5 m, 12 m/s		
	Positioning Weather Limit (Hs max, Vw max)	1.5 m, 12 m/s		
	Hoisting Weather Limit (Hs max, Vw max)	1.5 m, 12 m/s		

3.6 Other Equipment

Besides the summary of the equipment mentioned above, the other equipment considered for the O&M of any of the 5 wind farm cases are cable laying vessel, diving support vessel, internal crane for hoisting small components to and from the nacelle and davit crane on the platform capable of hoisting small components from the CTV's.

More information about the specifications of all the standard equipment can be referred in the Section 3.3 [26] of the ECN memo (ECN-Wind memo-12-003). Moreover, the use of CTV's, SOV's, helicopters and access system can vary depending based on the chosen O&M strategy.

Such combinations of equipment are used and corresponding case studies are detailed in Chapter 5.

4

O&M Strategy

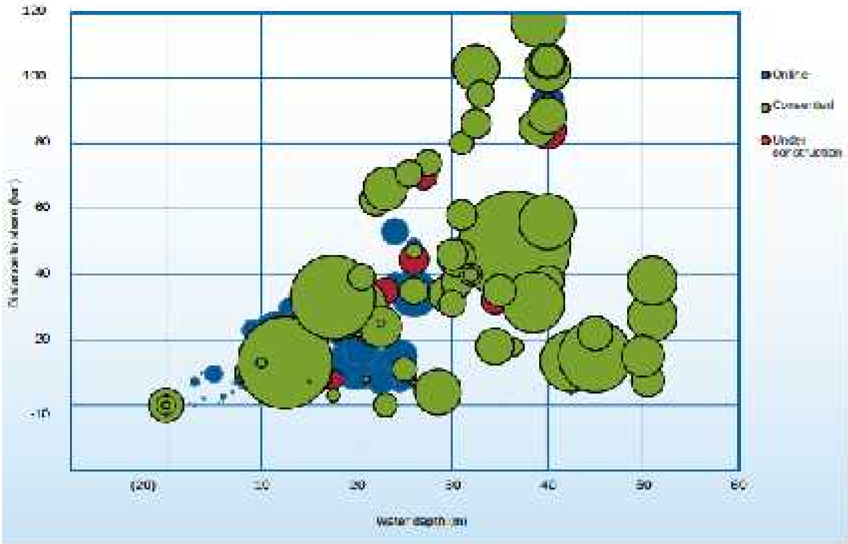
The offshore wind industry has seen the growth of wind farms both in terms of size and its distance from shore. The initial wind farms were operated with small catamarans (CTV’s) and gradually with the evolution of wind industry, purpose based maintenance vessels (SOV’s) are being manufactured and being used. Some of the main problems related to the Operations and Maintenance (O&M) strategy are: (a) More flexibility in terms of boarding the foundations in adverse weather; (b) More suitable offshore vessels at lower cost; (c) O&M crew stationed more close as possible to the wind farm [9]. Although there is a certain sense of understanding for the closer and small-medium sized wind farms, the large and far offshore wind farms in rough environment create challenges for O&M. Currently, there are no clear strategies defined for running cost-effective O&M for such wind farms and the current operators and owners of the wind farm are trying innovative and new methodologies [8]

This chapter is split up based on different O&M concepts. These includes both the existing O&M concepts which are widely accepted by the industry and the new age concepts which are foreseen for the future offshore wind industry. Additionally, the description of wind farms and equipment is referred from previous chapters. The concepts are classified based on whether the maintenance performed is shore based (Section 4.1) or offshore based (Section 4.2) or hybrid (Section 4.3). Moreover, a separate section for the maintenance of floating wind turbines is discussed in Section 4.4.

4.1 Shore based O&M Strategy

Shore based O&M Concepts refer to the maintenance base being located onshore. Moreover, it means that there is a certain harbour location from where the offshore wind farm is being operated. The technicians and the spare parts are also located onshore at the harbour location. This strategy is more applicable to the already existing wind farms which are relatively closer to shore. In 2014, the average distance to shore was in the range of 33 km and average water depth of 22.4 m [3]. However, some of the future wind farms are also planned in the same distance-water depth combination.

Figure 17: Graph illustrating the farm size, distance to shore and average water depth for offshore wind farms currently being online, under construction and consented [3].



Furthermore, as part of the shore based O&M concepts, it is noted that CTV's, access systems and helicopters are of limited use when there is a heavier spare part which needs to be transported and replaced. In this study, the crane limits and access vessel limits are set as 1 MT for 4 MW wind turbine machines and 3 MT for 8 MW machines. Hence, if the maintenance operation requires an effort of more than the limits mentioned, a bigger vessel in terms of jack-up barge is employed.

Some of the combinations which the operator could choose from when opting for a harbour based strategy are listed below. Additionally, the advantages and disadvantages of different strategies are evaluated.

4.1.1 CTV without access gangway

This is the most basic strategy which is implemented in the near-shore wind farms like OWEZ (in Netherlands) [27]. Following this strategy, the service staff is brought at offshore site by CTV's and transferred from the vessels to the turbines. As mentioned in Section 3.1, these vessels are able to operate at a maximum significant wave height of 1.5m. Hence, these strategies are expected to work only under calm waters. For heavy component (>1T) replacements, e.g. gearbox and generator, access to the turbine is provided via a gangway from a jack-up vessel.

Following this strategy for Wind Farm A (Section 2.1), the Availability (% energy based) is projected to be around 93.1% and the total O&M effort is estimated at 44.5 M€/year.

Following this strategy for Wind Farm A is challenging, as higher availability and corresponding lower O&M costs can be achieved from alternate solutions as indicated in Section 5.1.

4.1.2 CTV with access gangway

This strategy improves the performance of the CTV's by providing small ladder system or gangways. **Figure 12** in Section 3.2 illustrates such gangways. In principle, the CTV chosen should be able to accommodate such a ladder. These gangways improve the transfer both in terms of safety and technical specification. For more complex replacements, jack-up barge is still used. As an operator, the decision to include a gangway system in the maintenance strategy should be based on whether the extra O&M costs are recovered by higher power production or lower downtime or higher availability.

For Wind Farm B (Section 2.2) without an access gangway, the percentage yield-based availability is estimated at 94.40% with corresponding O&M effort being 35.85 M€/yr For the same wind farm, adding a gangway into the system improves the yield-based availability marginally to 94.8%. However, still reducing the overall O&M effort (35.14 M€/yr). The difference in case of Wind Farm B is less due to fewer number of turbines. The added value of such a strategy will be more prevalent with a wind farm (Wind Farm A) with more number of turbines. This is evident in the case study documented in Section 5.1.

4.1.3 CTV with Helicopter

This strategy has been in consideration for offshore wind since Alpha Ventus incorporated helipads and helideck in their offshore wind farm. In this strategy, the helicopters are used as an alternate equipment. I.e., if the wave height of 1.5 m is reached, the CTV's usage is replaced by helicopter transfer. Helicopters also provide the possibility to reach the wind farm under high wind conditions. The strategy is useful if the expensive lease cost of helicopters are covered by higher availability of the wind farm.

Section 5.2 shows the added value of the helicopter in the form of a case study (Wind Farm B).

4.1.4 Alternate harbour based strategies

The above mentioned harbour based strategies (Section 4.1.1-4.1.3) are more or less conventional and have been in operation for a large period of time. However, as an operator of the wind farm, there is always a possibility to be more innovative in choosing a strategy. One such example is listed in points below:

- A CTV with an access gangway is situated mostly near the Offshore High Voltage Station (OHVS).

- The technicians are always transported by the helicopter to the helipad situated at the OHVS.
- The spare parts up to 1T/4T based on turbine size (4MW/8MW) are stored in a storage place in OHVS. The spare parts are re-furnished with a feeder vessel every month or two months.
- In case of large repairs or replacement, jack-up vessels are used.

The strategy discussed above is a hypothetical one, but is definitely feasible if the operator wants to follow a harbour based strategy. The added value of such a strategy is that it reduces the travelling time, still providing safer transfer through CTV with gangway. Moreover, the smaller spare parts are also always available offshore. The said strategy will be more of added value for a wind farm with more than 75-80 turbines.

The harbour based strategies discussed above is one of the approach which currently the industry is approaching. However, with far-offshore (>50km) wind farms, the industry is more inclined to offshore based O&M strategy. These strategies are discussed in the next section.

4.2 Offshore based O&M Strategy

Offshore based O&M Concepts refer to the maintenance base being located offshore. Moreover, it means that there is a certain location at sea from where the offshore wind farm is primarily being operated. The technicians and the smaller spare parts are also located offshore. The strategy is more applicable for either the currently installed or future large offshore wind farms which are far-offshore (>50 km). For any operator, the high availability of a wind farm is of prime importance. As compared to shore based strategy, the offshore based strategy is definitely expensive. Hence, the combination of water depth, distance from shore and number of wind turbines justify the use of such a strategy. In addition, the safety and regulatory factors are key factors to influence the suitability of the offshore O&M strategy.

As part of the offshore based O&M options, two alternate strategies are suggested. Within each of the two options, different choices can be made. The strategies are explained in more detail in sub-sections below. Furthermore, similar to the shore based O&M concepts, the crane limits and access vessel limit are set as 1 MT for 4 MW wind turbine machines and 3 MT for 8 MW machines. Hence, a larger spare part is replaced by an alternate vessel (jack-up vessel).

4.2.1 Offshore Permanent Base

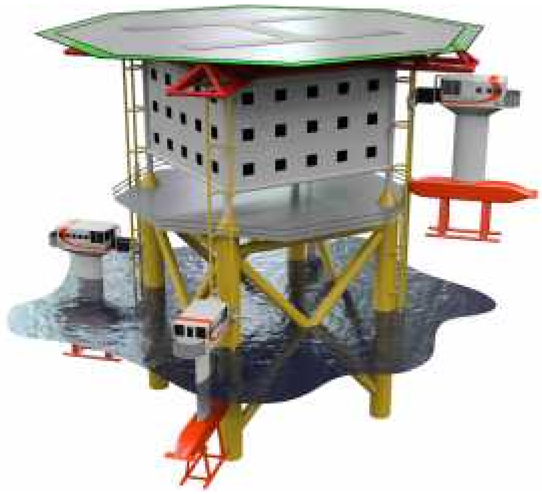
The largest structures existing in an offshore wind farm are the OHVS. Coupled with them, a permanent fixed base is also possible to be constructed. These permanent base are quite expensive to be constructed and installed. Hence, a profitable business case is required for it to be implemented. Horns Rev 2 chose for an offshore accommodation in their wind farm [30]. Such an offshore accommodation (**Figure 18**) can accommodate

30-40 technicians, house small spare parts and also provide a helipad location. As an operator, there is always an option whether to include the spare parts or not.

Figure 18: Permanent offshore base coupled with OHVS at Horns Rev2 wind farm [30]

Although the above permanent base platform is one of the options already been implemented, another possibility is to also have the CTV's situated near the offshore permanent base. This is much significant for further offshore wind farms (>50 km) which include permanent fixed base strucures as a strategy. Such a structure will provide faster reaction time and will limit the travelling time and weather delays caused due to the CTV's. Moreover, the CTV's can be physically parked at the offshore location. **Figure 19** shows an example of such a concept.

Figure 19: Concept based offshore base platform providing arrangement for CTV and helicopter [source: James Fisher Marine Services Ltd]



For wind farm C (Section 4.2.1), such a strategy is discussed in detail with the evaluation of overall KPI's (availability and cost).

4.2.2 Offshore Floating Base

Offshore floating base is an alternate to the fixed structure. Moreover, floating base refers to the use of Mother Vessel or Service Operating Vessel (SOV) as discussed in Section 3.4. As mentioned before, these SOV's are located offshore in the proximity of the wind farm. The benefit of a SOV over permanent base is that the SOV itself can involve itself into the maintenance activity and provides better performance abilities in terms of weather restrictions. Similar to the permanent base, the SOV's significantly reduce the time to access the wind plant for minor repairs or inspections. Additionally, because of reduced travel times, the fair weather windows are smaller, thus allowing for more opportunities that also reduce the plant downtime. The downside to employ such a strategy is high vessel costs and the long periods of offshore stay for technicians.

For an offshore floating base SOV, there is an option whether the provider of such a vessel gives a facility to store spare parts or not. Section 5.5 for Wind Farm D models a scenario with a floating base with CTV and spare parts stored on it.

The offshore based strategies discussed is another approach which currently the industry is slowly adopting. These strategies are expected to be play a significant role in future maintenance of wind farms. However, every industry needs to grow with innovative and efficient methods. Some of the cost-efficient methods (Hybrid based strategies) are discussed as part of the next section.

4.3 Hybrid based O&M Strategy

Hybrid O&M Concepts refer to the strategies with mixed character; composed of different elements. Currently, such strategies are not into practice, but possess a lot of potential considering the cost-effectiveness of these options. The strategies are elaborated more in the following sub-sections.

4.3.1 Multiple harbours

Current offshore wind farms are operated from a single harbour location. The common trend in each country is to make two or three offshore hubs for O&M. These locations are commercial harbours either dedicated for offshore wind or are shared with other sea-port business.

Besides these specific harbours, there are other small harbours which also have the potential to grow. They might not have the same infrastructure as the bigger ports, but can provide an opportunity to be more flexible onshore. Moreover, with this approach, we can split the maintenance resources (spare parts and vessels) between two harbour locations. As instance, for a future Dutch offshore wind farm in the Borssele area, Vlissingen can be used as a regular harbour for small maintenance activities and Rotterdam can be considered for large replacements. The large spare parts are much easier to be stored in a bigger port like Rotterdam.

The strategy especially can be employed if there is smaller port near the offshore wind farm and the travelling time can be reduced from the smaller-near harbour. Although, the approach requires efficient coordination between the two locations, the system definitely can be beneficial. Applying such an O&M strategy for Wind Farm B will lead to a potential saving of 0.5 M€/year.

4.3.2 Sharing Logistics

Offshore wind is an expensive industry. The owners and operators of the wind farm should look for opportunities sharing logistics between two or more wind farms operated either from shore or offshore.

Shore Based Strategy

Currently, many offshore developers e.g. Dong Energy, Vattenfall and E.ON and turbine manufacturers e.g. Siemens and Vestas have multiple wind farms close to each other. This shall provide an excellent opportunity to develop a strategy would allow to cluster the maintenance activity from the same harbour by sharing resources like vessels and equipment. Moreover, if the two wind farms also have the same company turbines, the spare part storage inventory can also be shared.

A case study for wind farm B is documented in Section 5.2, where the added value of the strategy is clearly evaluated. It is estimated that if we consider two identical wind farms of 400 MW, the sharing of resources and harbour will lead to a saving of around 14.5 M€/year for both wind farms.

Offshore Based Strategy

It is discussed in Section 4.2 that permanent structure or floating vessel as an offshore based strategy is expensive and the business case to choose for these options should be profitable.

This is similar to the above shared shore based strategy, the only difference being the operation base is offshore. This can be implemented considering the installation of many far-offshore wind farms with the same owner or operator (wind turbine manufacturers). This shall also provide an opportunity to the developers to quote for lower bid during the tender phase if they have an existing one or two wind farms in the same region under their portfolio.

Overall, the strategy will lower the O&M cost or the Life cycle cost of energy. For Wind Farm C, employing this strategy by sharing of a permanent base between two identical offshore wind farms will lead to a saving of 28.5 M€/year compared to two wind farms with their own permanent bases (case study of Section 5.3).

4.3.3 Ownership of Jack-up barge

Jack-up barge is an expensive vessel costing more than € 125K/day, with additional mobilisation and demobilisation costs. These vessels are employed for large replacement activities. In practice, these vessels are leased or contracted for a short period of time, when required. However, they have a very high mobilisation time (~30 days) and corresponding mobilisation costs (~€ 350K).

Instead of leasing these jack-up vessels, an alternate option is to actually purchase them. The advantage is overcoming the above mentioned points. However, these vessels are expensive themselves. This means the operator should be sure that he can recover the costs of jack-up vessel during the operational lifetime.

An example of employing this strategy is to use the jack-up vessel for all the wind farms under an owners portfolio. This way, the waiting time to arrange the jack-up vessel is minimum. Moreover, the operator can prioritize his replacements in different wind farms by owning such a vessel.

4.4 Floating Turbines O&M Strategy

O&M strategy for *floating turbines* require a modification to the conventional way of the maintenance operation. These alterations can be the direct experience from the already existing methods or finding new and innovative ways. In theory, floating turbines in general should have reduced offshore O&M costs (as compared to fixed structure) because there are no grouting or connection issues to deal with. However, there are too many unknown areas yet to be answered. Globally, there are only 5-6 floating turbines which are installed yet. These turbines are prototypes and are installed to gain experience in understanding the floating industry.

It is estimated that the floating wind has the potential to reach cost parity with fixed-bottom offshore wind during the 2020s as “the higher CAPEX of the platform, moorings, and anchors [is] negated by lower installation costs and lower OPEX driven by cheaper repair costs for major components” [7]. In other words, in case of a major failure the floating turbines can be towed back to port. Although the concept needs to be validated and economically feasible.

The cost benefit will also differ between concepts, largely due to the met-ocean limitations and conditions in which the structures can be towed back to shore and then, back to site. For semisubmersibles, which have greater tolerance to harsh conditions, it is likely that weather restrictions and downtime can be minimised and standard tug boats can be source quickly at low mobilisation costs. However, for TLP concepts, which are more sensitive to metocean conditions and may require a bespoke barge, the cost is likely to be higher. For spar concepts, the full structure will not be able to be towed back to port, but to a sheltered deep water area. Given that a heavy lift dynamic positioning vessels will be required anyway, spars could adopt the same repair procedure as conventional fixed-bottom structures. However, given the ability of spar-buoys to be towed in an upright position in challenging weather conditions, there may be a cost benefit in unhooking and transporting the vessel to reduce the amount of weather days and therefore the number of days for which the vessel must be chartered, as well as the associated downtime.[7]

Concerning the regular maintenance of the wind turbines, the operator can make a decision between regular CTV’s with ladders and SOV’s with gangways. The latter option also provides motion compensation for transferring crew and equipment which are necessary in the case of Floating offshore wind turbine. Section 5.5 demonstrates an O&M strategy for Wind Farm E.

5

Case Study

The optimal O&M strategy for an offshore wind will be the one where more suitable offshore vessels at lower costs are employed. Also, the O&M crew and spare parts are placed as close as possible to the wind farm. These different options are evaluated with *five* case studies performed for each wind farm. It should be noted that the case studies chosen for each of the wind farm is one of the many options indicated in Chapter 4. The modelling is performed using ECN O&M Access v1.0.

In general, following are the basic assumptions for the O&M strategy for all the case studies:

- **General**
  - Weather data for 5 chosen sites are representative of those locations.
  - The minimum length of a good weather window to perform a repair is 2 hours.

- **Components**
  - There are three type of maintenance performed- (a) *Corrective maintenance* where the action is performed after a failure happens; (b) *Calendar maintenance* where action is performed on a fixed regular schedule. This is done annually or twice a year as a part of preventive maintenance; (c) *Condition maintenance* where action is performed before a part breaks down. The repair is done based on the health of the system. This also requires a constant monitoring of different components.
  - The failure rate of components[5] (corrective) is constant over time.

- **Equipment**
  - There is a primary access vessel (with or without access gangway). The primary vessel can be either a CTV or SOV.
  - Additionally, by default, other equipment included as part of the O&M strategy are Jack-up vessel, Davit crane, Cable repair vessel and Diving

5 The wind turbine chosen for O&M modelling in ECN's default model (ECN-Wind memo-12-003) is a gearless turbine. However, the turbine in these case study is a geared turbine. Minor adjustments are done by including the right components and adjusting the failure rates accordingly.

support vessel. All these equipment are either vessel for replacement or internal crane.
  - More information about the specifications of all the standard equipment can be referred in the Section 3.3 [26]of the ECN memo (ECN-Wind memo-12-003).

- **Personnel**
  - There are 36 technicians for all the type of maintenance.
  - The technicians work for a 12 hour shift, starting at 7:00 a.m.

Based on these assumptions, the below case studies are performed. It should be noted that for each case study there are some changes made in the basic assumptions. These are indicated accordingly.

5.1 O&M Strategy Wind Farm A

Wind Farm A is an offshore site location which represents the existing trend of offshore wind farms being installed and commissioned. Specifically, it is a 400 MW wind farm with 4 MW turbines located 30 km from a Danish harbour. As part of the case study, for such a wind farm, harbour or shore based strategy (Section 4.1) is chosen. Moreover, out of the many options, CTV with gangway (Section 4.1.2) is considered for this case study. In addition to the basic O&M assumptions mentioned in the introduction of this chapter, some specific points to be noted are as follows:

- The regular corrective and calendar based maintenance (repair and replacement) are performed with a CTV possessing a gangway on it. These gangways just improve the capabilities and safety aspect of the CTV (as indicated in Section 4.1.2).
- The logistic and cost overview is referred from the **Table 9** (CTV-S + gangway).

Following the above O&M strategy, **Table 13** summarizes the output KPI’s.

Table 13: Output KPI's for Shore based strategy with access gangway

Output KPI's	
Availability (time)	94.6%
Availability (Yield)	94.3%
Costs per kWh	2.33 c€/kWh
Repair Costs	30.7 M€/yr
Revenue Losses	10.5 M€/yr
Total O&M Effort	**41.2 M€/yr**

From the above table, following points are to be noted:

- The use of CTV's with access gangway enables the technicians to work under rough weather conditions. This leads to an added time or yield availability of more than 1% as compared to the case where there is no gangway.
- The extra cost spent on including the gangway as part of the O&M strategy is recovered from lower revenue losses, and hence the total O&M effort is 3M€/yr less than the case without a gangway.

Overall, for wind farm A, the above mentioned strategy is quite suitable for an O&M operator. However, as indicated in Section 4.1 and Section 4.3, there are multiple options for such a wind farm following the shore based strategy or hybrid based strategy. Additionally, the operator is open to explore offshore based strategy as well, although it shall be quite expensive and not the most convincing option.

5.2 O&M Strategy Wind Farm B

Wind Farm B is an offshore site location which represents the future offshore wind farms in Western European countries. With the technological advancement of bigger turbines, the developers are definitely considering turbines of 7 MW or 8 MW. Hence, Wind Farm B is considered to be one of the future offshore wind farms with 50 turbines of 8 MW each and at a distance of 30 km. As part of the case study, for such a wind farm, harbour or shore based strategy (Section 4.1) and hybrid strategy (Section 4.3) is explored. Moreover, out of the many options, CTV with helicopter as an alternate access equipment (Section 4.1.3) is considered for the harbour based strategy in Section 5.2.1 and sharing of harbour or resource strategy (Section 4.3.2) is accounted for the hybrid strategy in Section 5.2.2.

5.2.1 Shore based O&M Strategy

Besides the basic O&M assumptions mentioned in the introduction of this chapter, some specific points for Harbour based strategy (CTV with helicopter) are:

- The regular corrective and calendar based maintenance (repair and replacement) are performed with a CTV. One of the CTV shown in **Figure 11** can be considered.
- The helicopter is provided as an additional equipment when the CTV is not able to operate. Note that the helicopter cannot be used when there needs to be a heavier spare part to be carried. Such adjustments have been made while modelling.
- The price of the consumables or spare parts have been proportionally increased to reflect it as a 8 MW turbine.
- The logistic and cost overview for the access equipment is referred from **Table 8** (CTV-XL) and **Table 10** (helicopter).

Following the above O&M strategy, **Table 14** summarizes the output KPI's:

Table 14: Output KPI's for Shore based strategy with helicopter as an alternate equipment.

Output KPI's	
Availability (time)	94.8%
Availability (Yield)	94.6%
Costs per kWh	1.53 c€/kWh
Repair Costs	23.7 M€/yr
Revenue Losses	11.6 M€/yr
Total O&M Effort	**35.3 M€/yr**

From the table above, following points are to be noted:

- Helicopter as an access system provides the opportunity to obtain higher accessibility to the wind farm. This leads to a marginal increase of 0.2% in time or yield availability compared to the case where just a CTV is used.
- The extra cost spent on including the helicopter into the O&M strategy is recovered from lower revenue losses, and hence the total O&M effort is 0.5 M€/yr less than the case without a helicopter.

Overall, it can be argued that the added value is marginal, however over the entire lifetime it accounts for around 10 M€. Moreover, it should be understood that these differences are under the logistic and cost assumptions considered for all the equipment. Further, such a strategy will show more added value if the number of turbines are higher or the distance of the wind farm from shore is more than 30 km.

5.2.2 Hybrid O&M Strategy

As indicated above, the other O&M strategy explored for Wind B is hybrid, namely, sharing harbour and resources between two different wind farms being operated from shore. **Figure 20** gives an impression of the location of the two wind farms following a hybrid strategy.

Figure 20: Impression of multiple wind farms employing a hybrid O&M strategy

As indicated in Section 4.3.2, this strategy will be of great value if the same developer or turbine manufacturer is handling two different wind farms from the same harbour. Besides the basic assumptions defined in the introduction of this chapter, the specific one w.r.t. this case are as follows:

- For modelling purpose, the two wind farms are assumed similar with the same set of turbines. Moreover, the overall wind turbine count has been increased to 100.
- Only a basic CTV is considered as part of the O&M strategy (Section 4.1.1). Further, after initial optimization, only 3 workboats are estimated to be sufficient for both the wind farms. Hence, the overall technician count is 36.
- All the equipment logistic and cost parameters are inserted as in **Table 8** (CTV-XL).
- The price of the consumables or spare parts have been proportionally increased to reflect it as a 8 MW turbine.

Following the above O&M strategy, **Table 15** summarizes the output KPI's:

Table 15: Output KPI's for Hybrid strategy, where sharing of resources and harbour is employed for two wind farms.

Output KPI's	
Availability (time)	94.8%
Availability (Yield)	94.5%
Costs per kWh	1.09 c€/kWh
Repair Costs	33.6 M€/yr
Revenue Losses	23.6 M€/yr
Total O&M Effort	**57.3 M€/yr**

From the table above, following are the key observation points:

- The percentage availability achieved for the two wind farms is quite high. This is even after the consideration of sharing the harbour and resources between the two wind farms.
- There is a saving in the overall repair cost, as the possibility of combining the maintenance operations are higher and hence leads to lower costs per kWh (1.09 c€/kWh for shared effort vs. 1.55 c€/kWh for an individual wind farm). Such hybrid strategies should be encouraged as this shall lead to substantial cost savings in the O&M effort. Moreover, the operation experience achieved from each wind farm leads to higher learning for the technicians and operators in general.

As was mentioned in previous case study, for this wind farm as well, there are various options to undertake the O&M. However, the optimum strategy is the one which leads to highest availability and lowest O&M costs. Unique strategy like sharing of resources has been investigated in this example and its added value clearly demonstrated.

5.3 O&M Strategy Wind Farm C

Offshore wind farms have increased in their capacity as the industry has developed. Currently, London Array (630 MW) and Gwynt y Môr (576 MW) in UK are the biggest installed (in terms of capacity) wind farms. By early 2017, Gemini offshore wind farm (600MW) in Netherlands will also be added in the list. Future offshore industry foresees even larger wind farms far-offshore from the harbour. Moreover, there is a certain region in North Sea which is not that deep (~30 metres) and still very far from coast. Considering such a scenario, Wind Farm C is modelled as a 800 MW far-offshore wind farm with 200 turbines of 4 MW each situated 150 km from the shore of UK, and in 30 metres of water depth. For such a wind farm, a dedicated offshore based strategy (Section 4.2) is better than the shore based strategy. More specifically, a permanent base with provision of spare parts and assisted by CTV (in the form of a daughter craft) is included in the O&M strategy (Section 4.2.1). Some of the assumptions accounted for this case study are:

- The permanent base structure is situated in the vicinity to the wind farm. The base provides an arrangement to park CTV at the offshore location. The offshore base also has a provision of storing all the spares below 1MT. The fixed cost of a permanent base is estimated to be €200K/yr.
- The spare parts are supplied by a Feeder vessel on a regular basis. The fixed costs of a feeder is assumed to be 0.5M€.
- The Spare part control strategy is applicable for all spare parts with <1MT. Although the spares are located immediately offshore, the re-ordering time is increased from 48 hours (default) to 144 hours.
- The time to organise in case of *inspection* and *repair* phases is reduced to half (e.g. 6 hours in default to 3 hours) in the case where CTV is used as the primary vessel.
- The logistic and additional costs of a CTV is referred from **Table 7**.

Following the above O&M strategy, **Table 16** summarizes the output KPI's:

Table 16: Output KPI's for Permanent base strategy with spares and CTV offshore

Output KPI's	
Availability (time)	93.6%
Availability (Yield)	93.0%
Costs per kWh	1.86 c€/kWh
Repair Costs	55.0 M€/yr
Revenue Losses	29.4 M€/yr
Total O&M Effort	**84.4 M€/yr**

From the table above, following points can be observed:

- The total O&M costs is substantial. This is due to the large count of wind turbines to be maintained.

- The availability (Time and Yield) is within the industry standards. This is possible only because of fast reaction time with the CTV's stationed offshore. The long travelling time and substantial period of weather delays is evaded in this case.

Constructing and operating wind farms with 200 turbines is a challenging and expensive proposition. Innovations in maintenance strategies are a must to operate such wind farms. One option for a developer is also to install larger machines which reduces the total number of turbines in a wind farm. Such a case study in discussed in the next section.

5.4 O&M Strategy Wind Farm D

Wind Farm D is a similar site as the case study of wind farm C. However, it is situated in another location of North Sea where the water depths are more (~50 metres). Also, larger 8 MW machines are considered for the 800 MW wind farm. It is considered that such a wind farm will require wind turbines with jacket structures for foundation. Furthermore, as part of the case study, an offshore based strategy (Section 4.2) is chosen for such a wind farm. In particular, as opposed to a permanent base structure (Section 5.3), a floating base in the form of Mother Vessel or SOV (Section 4.2.2) is considered for the O&M of the wind farm. The changes to the O&M assumptions as compared to the default case is iterated below:

- The SOV is always situated in the close proximity to the wind farm. It provides an arrangement to load CTV (daughter vessels). Also, it has a provision of storing all the spares below 3MT. The logistic and cost overview of a SOV is documented in **Table 11**. However, it should be noted that the CTV costs are included in the overall SOV costs.
- The spare parts are supplied by a Feeder vessel on a regular basis. The fixed costs of a feeder is assumed to be 0.5M€.
- The SOV has 36 technicians on board. 12 of them are equally distributed among the 2 daughter crafts and one for the mother vessel itself.
- The weather restrictions of the CTV and SOV are different and is referred from **Table 7** and **Table 11** respectively.
- The Spare part control strategy is applicable for all spare parts with <3MT. Although the spares are located immediately offshore, the re-ordering time is increased from 48 hours (default) to 144 hours.
- The time to organise in case of *inspection* and *repair* phases is reduced to half (e.g. 6 hours in default to 3 hours) in the case where CTV is used as the primary vessel. In case, the CTV's are busy or the weather restrictions are not permissible, the SOV will initiate the repair. Furthermore, during *replacement,* the SOV is assumed to act as the primary vessel.

Following the above O&M strategy, **Table 17** sums up the output KPI's:

Table 17: Output KPI's for Floating base with spares and CTV offshore

Output KPI's	
Availability (time)	94.5%
Availability (Yield)	94.3%
Costs per kWh	1.39 c€/kWh
Repair Costs	48.0 M€/yr
Revenue Losses	27.2 M€/yr
Total O&M Effort	**75.2 M€/yr**

From the above table, following facts are to be noted:

- The Costs per kWh are quite reasonable as compared to other case studies. Such a strategy demonstrates the course of future O&M.
- The wind farms are operated at high percentage availability (Time and Yield). This is possible due to the immediate reaction time of the SOV's and CTV's located offshore.

Numerous offshore wind farm owners and operators are choosing for SOV as a solution for maintaining their wind farms (as indicated in Section 3.4). Again, there are other alternatives to operate such an offshore wind farm as well. Hybrid offshore based strategies (Section 4.3) like sharing of SOV's or permanent base is also applicable for such wind farm, which will make the costs per kWh even lower.

5.5 O&M Strategy Wind Farm E

Floating offshore wind industry is under serious consideration, especially for sites either located far-offshore (>80 km) and deep (>40 m) or near-shore (20-30 km) and deep (>50 m). The countries which are pursuing interest in floating wind turbines are US, France, Norway, Japan, Korea. Japan has already installed 3 different floating prototypes. Wind Farm D represents a location in North Sea close to the Norway shore. The water depth at 20 km distance from shore is 200 m. It is a wind farm with 50 turbines of 8 MW each. Moreover, semi-sub technology is used for the floater concept.

As discussed in Section 4.4, floating O&M industry is still unknown on many accounts and the case study documented in this report is one representation of many options. Furthermore, following are the main assumptions:

- The regular corrective and condition based maintenance is performed by a small SOV. The number of technicians and corresponding cost of the SOV is modified to 36 and 10 €/yr as compared to the values in **Table 11**. The rest of the inputs are the same for SOV.
- For heavier replacements (spare parts> 3T), the complete structure is towed back to the port for quay-side maintenance, avoiding the need to charter expensive heavy lift vessels. This is performed using a towing vessel (Section 3.5). The logistic and cost values are used as indicated in **Table 12**.

- It is assumed that when the turbine is towed back, it does not affect the availability of any other turbine. Only the mooring lines of that turbine are disconnected.
- For spare parts less than 3MT, a feeder vessel is used on a regular basis to refill the small spare parts on the SOV.

Following the above O&M strategy, **Table 18** sums up the output KPI's:

Table 18: Output KPI's for O&M strategy for Floating offshore wind farm

Output KPI's	
Availability (time)	91.4%
Availability (Yield)	90.4%
Costs per kWh	2.82 c€/kWh
Repair Costs	41.6 M€/yr
Revenue Losses	20.6 M€/yr
Total O&M Effort	**62.2 M€/yr**

From the above table, following points are to be noted:

- The high Costs per kWh are due to the SOV as a regular maintenance vessel. However, due to the less number of turbines, the overall costs are still low as compared to Case Study D which also included SOV for O&M.
- The availability (Time & Yield) are both low as compared to other case studies. This is due to the higher downtime in the case of large spare part replacement (<3MT), as the turbine is towed back to the harbour. However, SOV present offshore allows for the immediate reaction time during smaller repairs and replacement.

Floating offshore wind is a developing part of the offshore wind industry. As mentioned before, there are various countries showing interest to install and commission floating turbines or farms in their respective countries. Given the role of turbine manufacturers in undertaking O&M activities, there is a pressing need for further engagement with OEMs, both to mitigate risk and ensure that floating concepts are designed appropriately.

6 Discussion

Existing accessibility models only consider significant wave height as the limiting factor, while in reality, offshore wind accessibility is a far more complex phenomena. Within the OM JIP project, a new accessibility model is defined, where metocean data are first translated to vessel hydrodynamics and then, vessel motion is translated to human fatigue and workability. In order to demonstrate the added value of this model it is essential to calculate the O&M costs and downtime using both models, the existing simple accessibility model and the improved one developed within the OM JIP project. The modelling results achieved in this report is performed with the existing model of accessibility.

The case studies discussed in the previous sections make it clear that choosing the most suitable O&M strategy for an offshore wind farm is not so straightforward. The costs associated with a certain addition to the conventional way of O&M, viz. access systems, SOV, helicopter, permanent base, etc. need to be compared with the potential cost savings in terms of increased availability. Moreover, the specifications of the wind farm (e.g. number, type of turbines and distance from shore) need to be taken into account which primarily affect the weather conditions. Furthermore, the advantages of a hybrid approach is also introduced and the added value demonstrated.

Overall, for each individual wind farm, a dedicated O&M concept needs to be chosen. Some of the questions that need to be asked while designing O&M strategies for any wind farm are :

- Shore-based or offshore-based?
- Multiple harbours or a single harbour?
- Which concept is the most efficient one?
- Which turbine size leads to the lowest costs?
- Is clustering with neighbours an option?
- Does helicopter helps to lower costs?
- Lease the jack-up barge or buy it?
- Access gangway or not?
- What to do with floating WTs?

These decisions were evaluated through the *five* case studies performed in this study. **Table 19** summarizes the output KPI's for each of the *five* wind farms and the corresponding O&M strategy.

Table 19: Summary of the O&M Strategies and corresponding KPI's for different wind farm configuration

Wind Farm	Wind Farm Specs	O&M Strategy	Availability (% Time, % Yield)	Costs per kWh[6]	Total Costs (O&M, Revenue loss)
A	400 MW (100*4 MW), 30 km from Danish coast, 20 m deep	CTV + access gangway	94.6%, 94.3%	2.33 c€/kWh	**41.2 M€/yr**
B	400 MW (50*8 MW), 30 km from Dutch coast , 20 m deep	CTV + helicopter	94.8%, 94.6%	1.53 c€/kWh	**35.3 M€/yr**
		Hybrid (shared harbour & resources)	94.8%, 94.5%	1.09 c€/kWh	**57.3M€/yr**[7]
C	800MW (200*4 MW), 150 km from UK coast, 30 m deep	Offshore permanent base	93.6%, 93.0%	1.86 c€/kWh	**84.4 M€/yr**
D	800 MW (100*8 MW), 150 km from German coast, 50 m deep	Offshore Floating base (SOV)	94.5%, 94.3%	1.39 c€/kWh	**75.2 M€/yr**
E[8]	400 MW (50*8 MW), 20 km from Norwegian coast, 200 m deep	SOV + towing vessel	91.4%, 90.4%	2.82 c€/kWh	**62.2 M€/yr**

With the above O&M modelling performed by ECN O&M Access, several smart and innovative concepts are assessed. Specifically, by adding an access system (as compared to only CTV) for Wind Farm A, a saving of **3 M€/yr** is achieved. Similarly, for Wind Farm B, as compared to the strategy with a CTV and helicopter, following a hybrid strategy led to a cost saving of **6.7 M€/yr.** For bigger and far-offshore wind farms, the added value of offshore permanent base and floating base (SOV) is highlighted. The advantage of these structures becomes more relevant when operated under a hybrid strategy. For Wind Farm C, sharing of permanent base will lead to cost saving of **28.5 M€/yr.** Last, the O&M of floating offshore wind turbines is touched upon. Although there is a lot of unfamiliarity with regards to floating turbines, one suitable solution for O&M is documented.

O&M modelling is of significant importance for the developer during the planning phase and actual operation. With this study, it has been shown that the O&M modelling can help support users in technology selection, CoE calculations, long term O&M planning, short term and end of lifetime decisions, etc. Under OM JIP, ECN O&M Access will be developed further, where vessel hydrodynamics and human fatigue will be included to better evaluate the actual performance and effort during operation and maintenance.

[6] The price of energy assumed for the *five* case studies is 13 c€/kWh

[7] The total revenue cost represents the overall effort for two wind farms of 400 MW each, as using hybrid strategy, the resources are shared between both. For a single wind farm representative of site B, the overall costs will be 28.6 M€/yr.

[8] Floating offshore wind farm

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