GL Garrad Hassan

OPTIMIZATION OF INSTALLATION, OPERATION AND MAINTENANCE AT OFFSHORE WIND PROJECTS IN THE U.S.

REVIEW AND MODELING OF EXISTING AND EMERGING APPROACHES

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AEP	Annual Energy Production
AHT	Anchor Handling Tug
BoP	Balance of Plant
CapEx	Capital Expenditure
CGS	Concrete Gravity Structure
CoG	Center of Gravity
CSC	Cuxhaven Steel Construction
DoE	U.S. Department of Energy
DP	Dynamic Positioning
DTTR	Direct Time To Repair
FTE	Full-Time Equivalent
GBS	Gravity Base Structure
GEBCO	General Bathymetric Chart of the Oceans
GL	Germanischer Lloyd
GL GH	Garrad Hassan America, Inc.
GPS	Global Positioning Satellite
HAT	Highest Astronomical Tide
HLCV	Heavy Lift Cargo Vessel
Hs	Significant Wave Height
LARS	Launch And Recovery System
LCoE	Levelized Cost of Energy
LOA	Length Over All
LoLo	Lift-on, Lift-off
LPC	Levelized Production Cost
MCA	Maritime and Coastguard Agency
MCE	Monte Carlo Engine
Metocean	Meteorological and Oceanographic
MOTS	Momac Offshore Transfer System
MTBF	Mean Time Between Failures
NCEP	National Centers for Environmental Protection
NCF	Net Capacity Factor
NDBC	National Data Buoy Center
NOAA	National Oceanographic and Atmospheric Administration
NSL	North Sea Logistics

O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OpEx	Operational Expenditure
OREI	Offshore Renewable Energy Installations
OSV	Offshore Support Vessel
OWA	Offshore Wind Accelerator
OWAS	Offshore Wind Access System
OWPMS	Offshore Wind Power Marine Services
PTS	Personal Transfer System
RIB	Rigid Inflatable Boat
RoRo	Roll-on, Roll-off
ROV	Remotely Operated Vehicle
SEP	Self-Elevating Platform
SES	Surface Effect Ship
SPMT	Self-Propelled Modular Transporter
SPS	Subsea Protection System
SWATH	Small Water-plane Area Twin Hull vessel
SWL	Safe Working Load
TAS	Turbine Access System
TE	Theoretical Maximum Energy
TIB	Turbine Installation Barge
TLP	Tensioned-Leg Platform
VFR	Visual Flight Rules
WCW	WindCat Workboat

EXECUTIVE SUMMARY

The United States Department of Energy (DOE) awarded a grant to GL Garrad Hassan (GL GH) to investigate the logistics, opportunities, and costs associated with existing and emerging installation and operation and maintenance (O&M) activities at offshore wind projects as part of the DOE's program to reduce barriers facing offshore wind project development in the United States (U.S.). This report (the Report) forms part of Subtopic 5.3 "Optimized Installation, Operation and Maintenance Strategies Study" which in turn is part of the "Removing Market Barriers in U.S. Offshore Wind" set of projects for the DOE. The purpose of Subtopic 5.3 is to aid and facilitate informed decision-making regarding installation and O&M during the development, installation, and operation of offshore wind projects in order to increase efficiency and reduce the levelized cost of energy (LCoE).

Given the large area of U.S. territorial waters, the generally higher mean wind speeds offshore, and the proximity to the coast of many large U.S. cities, offshore wind power has the potential to become a significant contributor of energy to U.S. markets. However, for the U.S. to ensure that the development of offshore wind energy projects is carried out in an efficient and cost-effective manner, it is important to be cognizant of the current and emerging practices in both the domestic and international offshore wind energy industries. The U.S. can harness the experience gained globally and combine this with the skills and assets of an already sizeable onshore wind industry, as well as the resources of a mature offshore oil and gas industry, to develop a strong offshore wind sector. The work detailed in this report is aimed at assisting with that learning curve, particularly in terms of offshore specific installation and O&M activities.

This Report and the Installation and O&M LCoE Analysis Tool, which were developed together by GL GH as part of this study, allow readers to identify, model and probe the economic merits and sensitivities of various approaches to construction and O&M practices, using illustrative offshore projects across a wide range of alternative offshore development areas located in U.S. waters. The intention is to assist decision-makers in clearly understanding the relative economic benefits of both conventional and novel construction installation methodologies and maintenance techniques within the critical parameters of a Project's LCoE.

Review of Installation Methodologies and Vessels

The installation of offshore wind projects can be carried out using a large variety of onshore and offshore procedures and activities. To date, many of the techniques, approaches and vessels employed can be traced back to other offshore industries, most notably the offshore oil and gas sector. However, with the recent rapid global expansion in offshore wind, the industry is now readily exploring new, more efficient and cost effective options for installation; from minor improvements in the handling and speed of operations, to the production of purpose-built vessels and the implementation of novel installation methodologies. These proposed alternatives each place different demands upon the vessels, cranes, equipment, and components during the installation. Early stage understanding of the merits and weaknesses of these alternatives is of vital importance to the development of individual projects, as well as the safe and successful growth of the offshore industry in general.

GL GH has investigated standard and emerging practices for offshore wind farm installation, covering all the major components of a project. In cases in which a wind farm component has multiple installation options (turbine rotors for example, with single blade, 'bunny-ears' (two blade), and full rotor installation options), each option has been assessed with focus on the following:

- Level of Standardization: Is the method proven and is there experience with its application?

- Installation Plant Availability: Are existing vessels and installation equipment, either inside and outside the U.S., suitable for this method and widely available?
- Installation Costs: how expensive is the charter of the installation vessel fleet and related equipment?
- Weather Sensitivity: how sensitive is the method to weather conditions?
- Port Requirements: how significant are the requirements on the ports, and how likely is this to be achieved with existing infrastructure?

Only those methodologies that are considered reasonably low impact in each of the above criteria have been evaluated further by GL GH utilizing the LCoE Analysis Tool. This allowed GL GH to focus only on methodologies which are likely to actually be implemented commercially.

GL GH has also reviewed current and proposed heavy lift transport and installation vessels with a view to understanding the types of vessel that may be available to the U.S. Offshore Wind Market, considering both U.S. Flagged and Foreign Flagged vessels. There are currently significant restrictions in place on the vessels that are able to operate in U.S. waters, due to the Merchant Marine Act of 1920 (commonly known as the Jones Act). The Jones Act is a United States federal statute that regulates maritime commerce in U.S. waters and between U.S. ports. It requires that all goods transported by water between U.S. ports be carried by U.S. Flagged ships. However, the Jones Act does not prevent the use of non-U.S. Flagged vessel for static installation purposes, such as pile driving or erection of a wind turbine, provided the vessel does not move from one station to another with merchandise (e.g. foundations or turbine components, etc.) on board. For the reasons mentioned above, GL GH has considered both Jones Act compliant and non-compliant vessels.

Added to the vessel constraints imposed by the Jones Act is the limitation for potential installation vessels when considering a deployment of offshore wind farms within the Great Lakes. Access to the Great Lakes via the locks within the St Lawrence Seaway poses a major constraint for installation vessels.

Review of O&M Methodologies and Vessels

Maintenance of offshore wind projects requires a whole new approach compared to the oil and gas sector, given the size and complexity of offshore wind farm installations. However, to date standard boat-access methodologies have been employed in Europe to transfer technicians on to wind turbines, with helicopter access being utilized more widely in recent years. Significant effort has been applied to the task of improved wind turbine access, given the move further offshore into more demanding weather and sea conditions. These efforts have focused on specialized access systems, which themselves operate on boats of varying sizes and capabilities.

GL GH has investigated standard and emerging practices for offshore wind turbine and offshore sub-station access, covering all the major vessels and types of access systems. This review includes systems which are currently under development in Europe and takes into account vessels capable of accessing wind farms in surface ice, which presents conditions similar to those likely to be encountered at offshore projects located in the Great Lakes region.

Unlike the installation methodology review which focused on those approaches liklely to be commercially implemented, no down-selection of access methods was required as part of the work presented here. All options have been modeled, within varying wave height accessibility limits, to capture the performance parameters of the full range of both vessels and onboard access systems.

Development of the Installation and O&M LCoE Analysis Tool

All offshore operations are limited by the weather conditions under which they can be safely conducted. Therefore the location of the project, the season during which each phase of installation is carried out and the vessel and installation methodology adopted for that phase of the work are likely to have a strong influence on the degree of accrued weather downtime and associated risk and cost. It is therefore critical for accurate assessment of potential installation and O&M approaches to carefully evaluate the anticipated site conditions as well as the limits thereby placed upon each operation and vessel considered. In order to assess this level of risk and costs, GL GH has undertaken detailed time-domain modeling of offshore installation and O&M across U.S. waters to inform a bottom-up costing of wind farm installation capital costs and O&M operational costs. The following sections describe the modeling approach undertaken by GL GH.

Metocean Conditions Analysis

Given the large extent of U.S waters, for purposes of this review, GL GH has divided the area of the contiguous U.S. into eight discrete regions, as presented in Figure 1. Metocean characteristics for each region have been developed using measured wind and wave data from the National Oceanographic and Atmospheric Agency (NOAA) [www.ncep.noaa.gov, www.ndbc.noaa.gov]. Mean annual significant wave height is expected to vary between 0.6 m in the Great Lakes and 2.6 m in the Pacific Region. There are not broad variations in annual mean wind between regions, although the Atlantic and Pacific regions can be considered to have higher annual mean wind speeds. For Installation & O&M, long-term means are of less relevance and these activities will be affected by hourly wind speeded variation. Activates in the Gulf of Mexico will there be more affected during hurricane season comared to other regions, even though it has a lower mean wind climate. Ice coverage data has also been procured from NOAA for the Great Lakes region, which may be largely covered by ice for several months in particularly cold years.

The above data have been used to derive hourly time series of metocean and ice coverage for each of the regions. These data have been used within the models described below to assess the relative cost impacts and benefits of different installation and O&M operations methods within each region.

Figure 1: Division of U.S. Coastal Regions

From each of the 8 regions, a total of 33 years of meteorological data have been analyzed to determine the probabilistic delays in installation and O&M activities related to weather. The 33 years of metocean data sourced for each region are required in order to provide converged, long-term results for models containing stochastic elements indicative of the regions of interest.

O2C Installation Modeling

GL GH utilized its analytical, in-house simulation tool known as the O2C (Optimization of Offshore Construction) Model in order to simulate the build-out of offshore wind farms, considering the shortlisted installation methodologies identified as part of the review and screening process described above. The O2C Model provides robust estimates of installation downtime due to operational constraints, providing a realistic build schedule. Constraints consist of both weather limitations on activities as well as the spatial interaction between activities at locations within the offshore wind farm.

The O2C Model utilizes the hourly metocean time series developed for each region to characterize the metocean condition at the wind farm site. Each operation is defined (where an operation might be, for instance, lifting a wind turbine nacelle into position on the wind turbine tower). Each operation has an associated set of wind and wave limits and is modeled in the time domain against the metocean time series to determine the overall duration of each operation accounting for any delay associated with the weather downtime. Consideration is given to operations which can only be completed in an uninterrupted weather window, and operations which can be broken down into weather windows smaller than the operation duration. Operations are then collated into a sequence to define an activity, with the interaction between activities modeled to estimate any delays due to limited vessel availability or preceding activities limiting access to a wind turbine location. Modeled offshore construction activities include:

- Offshore sub-station installation;
- Export cable installation;
- Wind turbine foundation installation;
- Inter-turbine array cable installation;
- Wind turbine installation, and;
- Offshore substation and wind turbine commissioning.

Day-rate and mobilization costs estimates are combined with the durations calculated for each activity to determine a bottom-up cost for the installation of the wind farm. The ultimate user has the ability to amend these cost assumptions within the tool.

While an established set of installation methodologies has been modeled, a key consideration within the final Installation and O&M LCoE Analysis Tool is that the ultimate user can amend the operations and/or their weather limitations in order to better assess any installation process improvements.

O2M Operations and Maintenance Modeling

GL GH utilized the O2M Model also to simulate the scheduled and un-scheduled maintenance of offshore wind farms. The O2M Model is used to predict wind farm availability and the associated cost of O&M activity run in the time domain, the overall approach being based on a Monte Carlo simulation, with turbine failures occurring on a stochastic basis. Delays associated with poor weather are simulated using metocean data derived for each region, comprising of significant wave height (Hs) and concurrent wind speed. The relationship between Hs and wind speed is therefore intrinsically captured enabling the modeling to simulate the effect of poor wind farm accessibility during periods of high wind and hence high production potential. Modeled offshore operations and maintenance access methods include:

- Port-based work boats;
- Port-based work boats plus helicopter;
- Mothership with daughter craft;
- Offshore based personnel with work boats;
- Jack-up vessel (doubling as an offshore accommodation platform);
- Port-based work boats plus hovercraft (for Great Lakes Region only), and;
- Other emerging vessels and transfer solutions.

The consideration of future technology development is of vital importance for the analysis of a potential deployment of offshore wind farms in U.S. waters, for this reasons it is possible to vary the capabilities of work boats, daughter crafts and the use of different access systems.

In order to estimate the total operational costs it is necessary to make several assumptions on the cost of elements within the O&M infrastructure as well as other non-technical items such as insurance and administration. GL GH has made the following basic costing assumptions based on in-house knowledge and market intelligence:

- Project insurance
- O&M service provider profit & risk margin
- Seabed and transmission network system fees and leases
- Costs related to technicians consist mainly of salaries, medical cover, pension, subsistence, training, and equipment.
- Onshore administration, staffing, office space and parts store
- Access vessel
- Jack-up strategy (open-market, call-off, ownership)
- Spare parts and consumables

The ultimate user has the ability to amend these costs assumptions within the tool.

Annual Energy Production Modeling

In order to determine relative LCoE in evaluating potential installation and O&M options, it is necessary to derive the net energy production of the project under consideration. A robust estimate is required to capture the effects of wind climate, wind turbine performance and energy loss factors (notability wake losses and wind turbine availability). GL GH has developed a set of functions to calculate the annual energy production, taking into account each of these drivers. The wind climates have been informed from the meteorological climates derived for each region, suitably scaled to 100 m above mean sea level. Wind turbine characteristics have been developed for two generic machines, specifically 4 MW and 6 MW, with the aim of capturing the trend toward increasing rated capacity and rotor size in offshore wind turbine technology.. The GL GH WindFarmer wake model was used to calculate the net annual energy production (after wake losses only). Further losses were considered, specifically:

- Wind turbine availability losses: Losses associated with wind turbine failure are estimated from the O&M modeling conducted and is dependent not only on the selected O&M strategy, but also the regional metocean climate.
- Electrical losses: Both inter-array and export electrical system losses are considered. In the LCoE Analysis Tool, these losses are informed by the user.
- Balance of plant availability: Losses associated with failures of the electrical balance of plant are considered. In the LCoE Analysis Tool, this loss is provided by the user.
- Other losses: Consisting of items such as: wind turbine bladed degradation, underperformance losses, high-wind hysteresis loss, etc.

The above losses were captured as part of the overall net energy production function, with a single function developed for each wind turbine option, for each metocean climate, within each region. This resulted in a total of 48 functions within the LCoE Analysis Tool.

Levelized Cost of Energy Calculation

To determine an offshore wind farm's Levelized Cost of Energy, GL GH has used the Levelized Production Cost (LPC) metric. LPC allows for the costs benefits to be realized within the context of complete project capital and operational expenditure.

Capital expenditure is derived by summing the project design, supply, and installation costs, namely:

- Electrical balance of plant design and supply;
- Support structure design and supply;
- Wind turbine supply; and
- Installation.

For the purposes of this study, the installation contribution to the project CapEx is provided by the installation model, while the design and supply elements (the first 3 items in the above list) are provided as inputs by the user.

Other significant cost items that are considered part of the overall CapEx estimate are:

• Project Development Costs	(assumed at 2.0% of CapEx);
• Project Management Costs	(assumed at 2.0% of CapEx);
• Construction Insurance	(assumed at 1.0% of CapEx); and
• Legal & Financing Costs	(assumed at 1.0% of CapEx).

Operational expenditure is derived from the O&M OpEx Model and annual energy production is derived from the Annual Energy Production (AEP) Model. These values are taken directly into the LPC function.

Key Results from the Study

To understand the variation in estimated offshore wind farm LCoE; and to understand the influence installation and O&M strategies have on overall cost, GL GH has utilized the LCoE Analysis Tool to investigate of a number of case-studies cases across U.S. The LCoE of a particular case depends on a combination of selected parameters, specifically:

- U.S. climatic region;
- Mean annual significant wave height (Hs);
- Mean annual wind speed (Ws);
- Project configuration (No. of wind turbines, capacity, etc.);
- Distance to installation port;
- Distance to O&M port;
- Foundation installation methodology;
- Array cable installation methodology;
- WTG installation methodology;
- O&M access strategy;
- WTG reliability;
- O&M jack-up contracting strategy;
- Significant wave height (Hs) and cruising speed limits of work boats; and
- O&M repair crew resource.

The number of parameters that can be independently varied within the LCoE Analysis Tool allows user consideration of an extensive number of scenarios. Therefore the results section of this report focuses on some key headline results that outline important sensitivities in terms of cost of energy, installation capital expenditure (CapEx), operational expenditure (OpEx), installation activity durations, and wind farm availability. To achieve this, a generic 504 MW wind farm has been assessed, considering the following fixed parameters:

- Distance to installation port: 75 Nm
- Distance to O&M port: 20 Nm
- Foundation installation: Jacket – Pre-piled – Driven – Feeder Vessel
- Array cable installation: Jetting
- Wind turbine installation: Single Blade Installation
- WTG reliability: Central

- O&M jack-up contracting strategy:	Open Market
- O&M jack-up lead time:	30 days
- Work boat Hs capability:	1.25 m
- Work boats speed:	20 knots

The following sensitivity studies were conducted with respect to LCoE, considering the above fixed parameters and varying the following:

- In-region metocean climate severity
- Inter-region metocean climate
- Distance from installation and O&M port
- Project configuration (No. of WTGs)

It should be noted that the O&M access strategy and repair resource (see Section 7.2.1) have been optimized for each sensitivity analysis.

The following figures highlight the results of these sensitivity analyses and show the contribution of the installation CapEx and annual OpEx to the total LCoE. Not shown are the development, design, supply, or management costs. The total LCoE value is also provided for comparison.

Note that by looking at the levelized CoE, the CapEx is annualized over the life of the project and added to the Opex, rather than presenting the CapEx as a lump sum. The figures below show these values in annual $/MWh.

In-region metocean climate severity

It is clear that installation CapEx and project OpEx increase non-linearly with more onerous climates, as metocean conditions exceed operation weather limitations more frequently, resulting in further weather delay and higher vessel expenditure. Of note is the contribution of installation CapEx and project OpEx to the overall project LCoE when varying climate severity, with a significant greater contribution in harsher climates.

Overall LCoE [$/MWh]	179	193	235
MWS 100m [m/s]	6.6	8.1	10.2
Mean Hs [m]	0.59	1.26	1.93

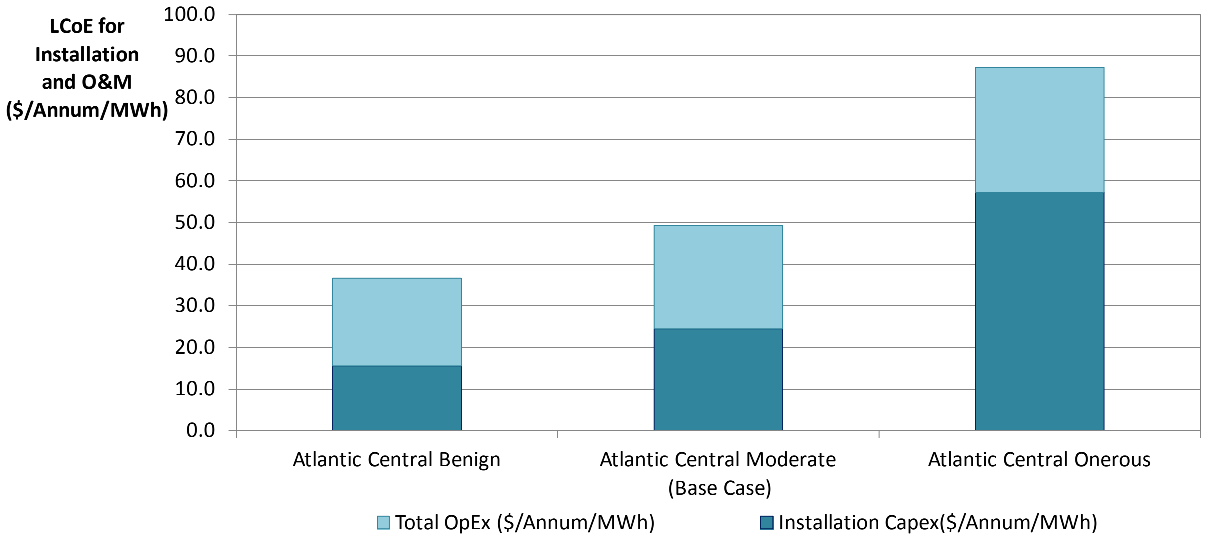


Figure 2: Levelized Cost of Energy for Installation and O&M within Climatic Zone

Inter-region metocean climate

It can be seen that installation CapEx and project OpEx increase with the more severe regional metocean climates, where conditions exceed operation weather limitations more frequently, resulting in further weather delay and higher vessel expenditure. Of note is the variation in LCoE for the modeled Atlantic regions, which share the same mean significant wave height. The reason for this is in the exceedance/persistence of the sea-states, with the southern region having the benefit of a greater frequency of longer weather-windows of relatively benign weather.

Overall LCoE [$/MWh]	193	192	184	190	186	199
MWS 100m [m/s]	8.4	8.4	8.4	8.5	8.5	8.1
Mean Hs [m]	1.26	1.26	1.26	1.23	1.23	0.73

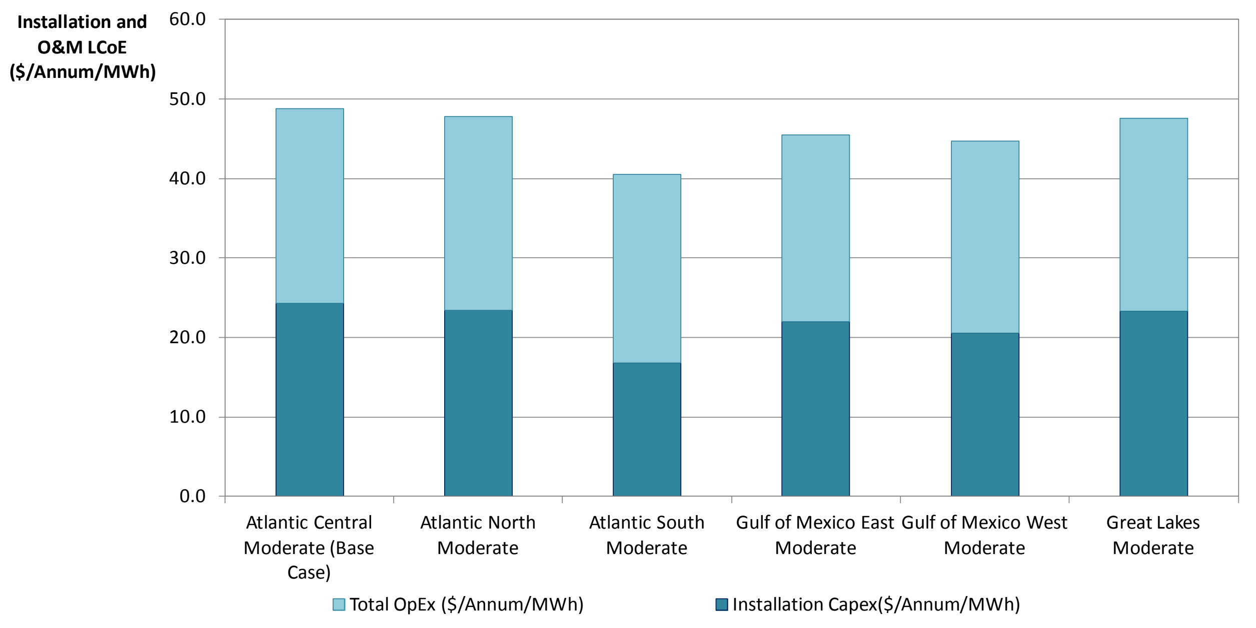


Figure 3: Levelized Cost of Energy for Installation and O&M with Varying Climatic Zone (126 x 4MW WTGs)

Another point of note is the higher costs associated with the Great Lakes Region, which has the lowest mean Hs of all regions. The high cost is a direct result of the occurrence of surface ice reducing the period available for installation activities. It should be noted that GL GH has assumed that vessels remain on stand-by during icing periods (i.e. a cost to the project). The main reason for this is the unpredictable nature of the sea ice, which may preclude the planning of demobilization and remobilization during winter months. The isolated nature of the Great Lakes will also make it more difficult for specialist installation vessels to move to other projects in other regions during these periods, given the limited access to the Lakes.

By far the greatest influence to LCoE is installation CapEx within the Pacific regions. The LCoE Analysis Tool requires that installation weather windows are continuous, and this requirement is most difficult to fulfill in the Pacific. While project O&M costs are also greater than for the other regions, they are a relatively minor contributor to the LCoE costs in the Pacific regions. This is likely due to the reduced requirement for sustained, long weather windows for wind turbine O&M works as well as the pre-optimization applied under this analysis, allowing the model to adopt more capable vessels and helicopters in a bid to mitigate the severe metocean climate.

Overall LCoE [$/MWh]	193	974	665
MWS 100m [m/s]	8.4	8.1	8.1
Mean Hs [m]	1.26	2.25	2.25

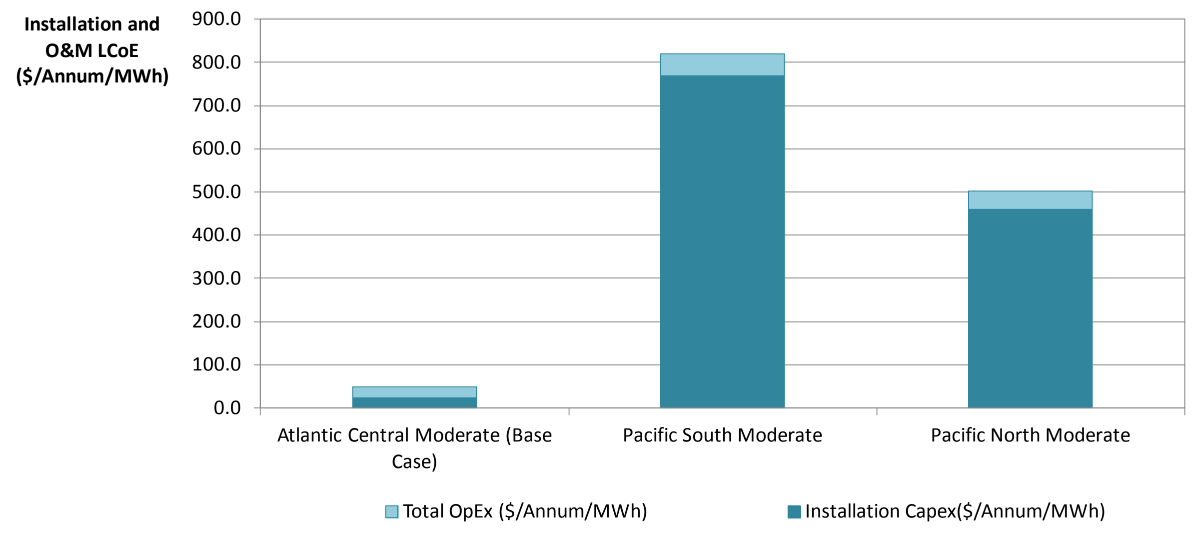


Figure 4: Levelized Cost of Energy for Installation and O&M with Varying Climatic Zone (126 x 4MW WTGs)

Distance from installation and O&M port

It is clear that O&M costs are sensitive to changes in distance between the wind farm site and the O&M port. This is a result of the increased transit times as well as the strategic shift to the more expensive, offshore-based strategy for the 150Nm case. In the case presented here, installation costs are less sensitive to distance between the wind farm site and the installation staging port, given the use of feeder vessels to transport foundations to the wind farm site, which allows for time savings compared to using the installation vessel as the transport medium. In the figure below, the distances are given in nautical miles (Nm) in the format “(distance to installation port) / (distance to O&M port)”.

Overall LCoE [$/MWh]	190	193	207
Installation Port [Nm]	25	75	150
O&M Port [Nm]	10	20	70

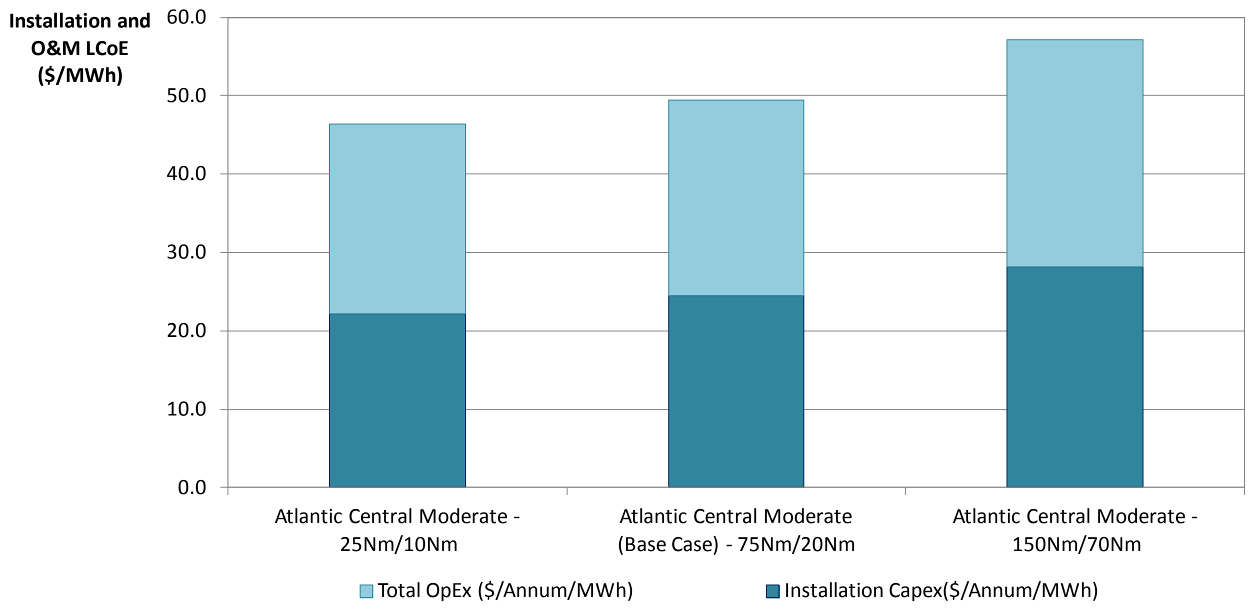


Figure 5: Levelized Cost of Energy for Installation and O&M with Varying Distances to Ports

Project configuration (No. of WTGs)

It can be seen that significant cost savings can be achieved through the installation of fewer, larger wind turbines, taking advantage of economies of scale. It should be noted that the 6 MW wind farm configuration has an energy capacity factor of 47.8%, compared to 45.7% for the 4 MW wind farm configuration, indicating that wind turbine technology, combined with greater spacing of wind turbines, for a given project area, can have a significant impact on lowering overall LCoE.

Overall LCoE [$/MWh]	193	166
WTG Capacity [MW]	4	6
No. WTGs	126	84

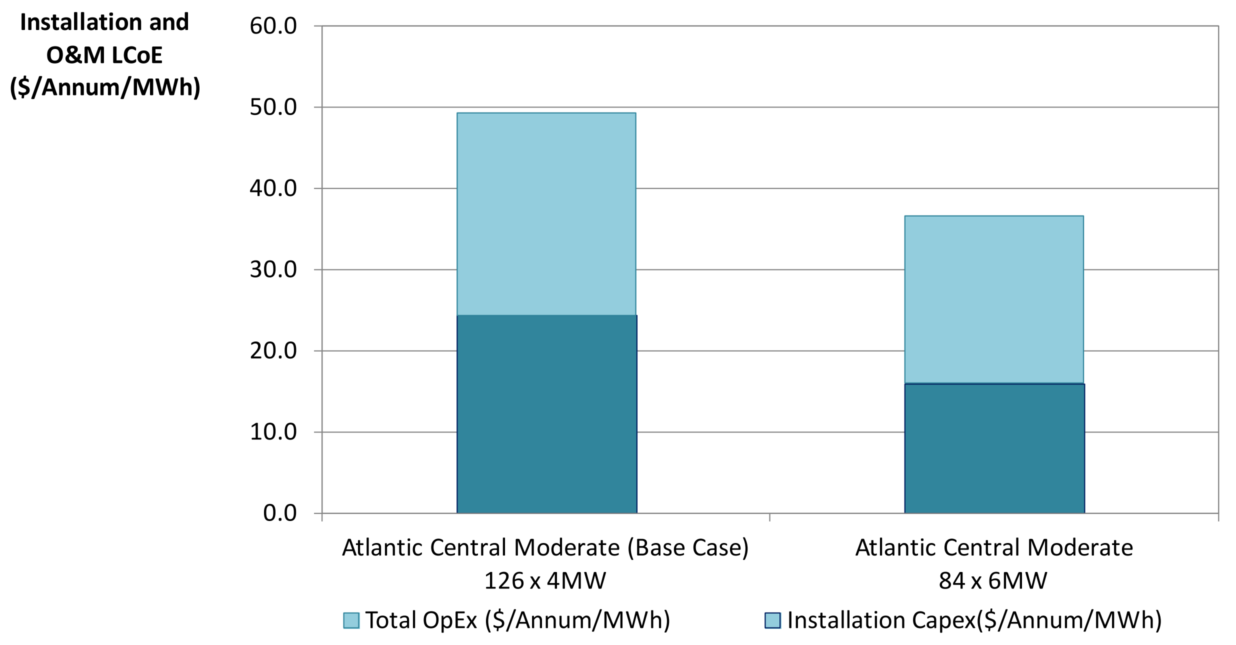


Figure 6: Levelized Cost of Energy for Installation and O&M with Varying Project Configuration

The LCoE for each of the installation methodologies is presented in the figure below, with a breakdown provided for each activity to reflect interdependencies between the foundation installation and the installation of other plant. As can be seen in the figure, foundation installation accounts for a substantial portion of the total installation cost of an offshore project, followed by the installation of the offshore substation and the wind turbines. It should be noted, however, that the durations used to inform these costs are representative of the 504 MW generic project under consideration as part of this study, and therefore these durations and costs need to be customized for a specific project and should not be viewed as absolute for all offshore wind projects.

In addition to the above spatial assessment of LCoE within U.S. waters, an assessment of the influence of foundation installation methodology has been completed. GL GH has maintained the base case assumptions, detailed above, and since the type of foundation doesn’t affect the O&M strategy, this has also been kept constant, with foundation installation methodology being the only variable considered.

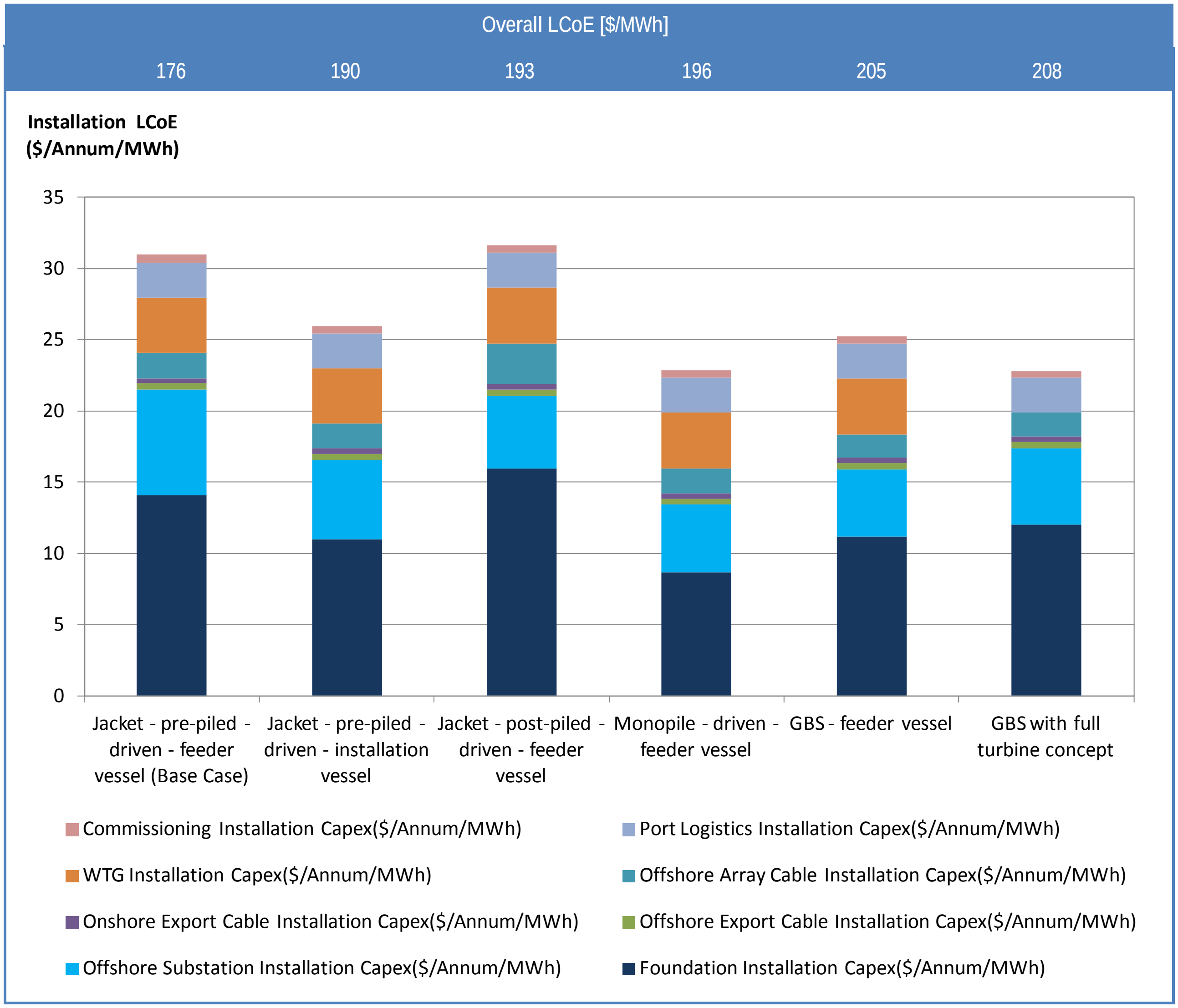


Figure 7: Levelized Cost of Energy for Installation and O&M with Varying Installation Methodology

GL GH has further investigated the impact of varying O&M strategy on total O&M cost, where total O&M cost is defined here as the sum of the direct costs (cost of implementing the O&M strategy) and lost production costs (an opportunity cost, where a higher project availability results in a lower lost production cost). GL GH has varied the access methodology and optimized technician repair crew resourcing accordingly, while maintaining all other base case assumptions.

It can be seen that a helicopter in support of workboats appears to be the most favorable access strategy in terms of overall project economics. Interestingly, the OpEx associated with the helicopter access strategy is less than that of the port-based work boats, despite the additional costs associated with a helicopter. This is due to the reduced optimal number of repair crews required when a helicopter is utilized due to the improved accessibility and therefore greater resource efficiency. The advanced access system and night-time working assumptions associated with the “floatel” (floating hotel) strategy have resulted in this approach providing the highest availability. However, the reduction in lost production is insufficient to mitigate the substantial costs associated with owning and operating the floatel and daughter crafts. While somewhat less expensive than the floatel, the two alternative fixed offshore base options appear to provide the least economically attractive solutions overall. This can be attributed to the limited accessibility associated with the use of work boats in conjunction with these offshore bases.

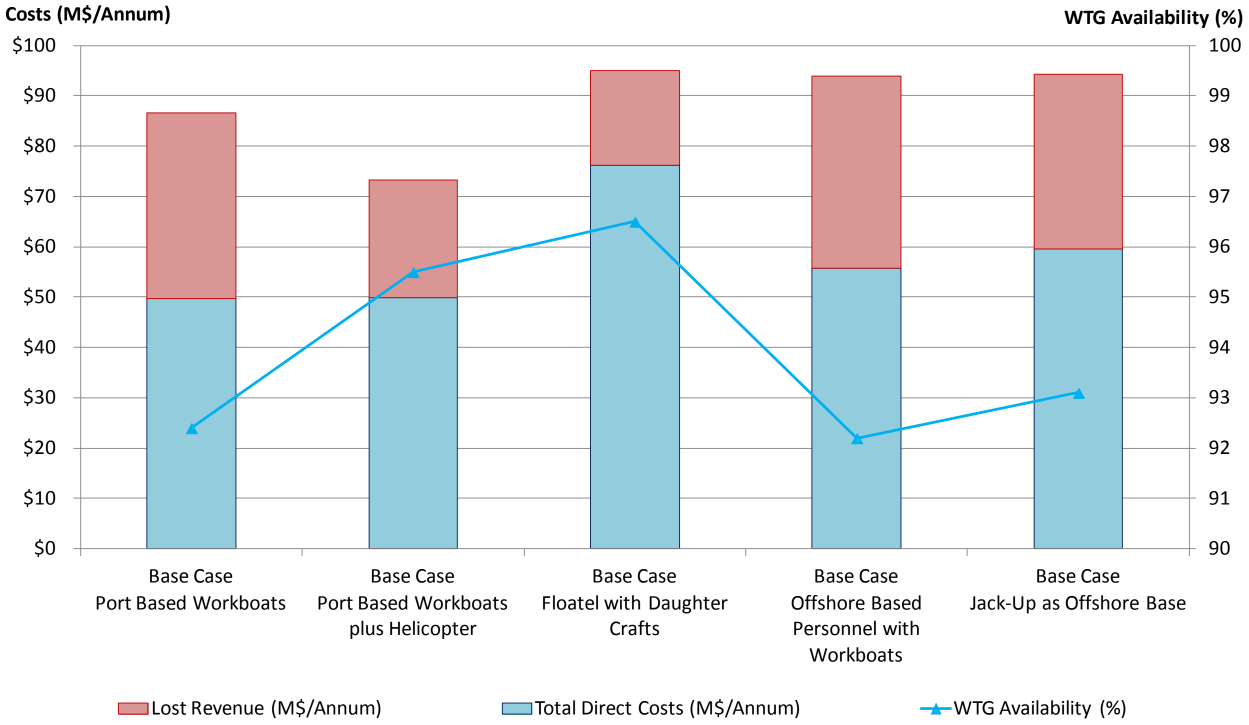


Figure 8: O&M Costs and WTG Availability with Varying O&M Access Strategy

Conclusions

GL GH has developed an Installation and O&M LCoE Analysis Tool to investigate the influence of the installation capital costs and operations and maintenance costs on the overall cost of energy of offshore projects within U.S. waters. The Analysis Tool also allows individual users to model any combinations and variations of methods and technical solutions during the project planning process in order to assess the relative and compound LCoE impacts of potential installation and O&M approaches before major decisions are made.

As part of this investigation, GL GH has reviewed current 'state-of-the-art', as well as proposed future practices and trends for offshore wind farm installation and O&M. This technical assessment, combined with a review of meteorological and metocean conditions around the U.S. coast and the Great Lakes, was taken forward as part of an intensive modeling exercise to develop costs for these aspects of offshore wind projects. These costs have been combined with other assumed capital and operational costs within the Installation and O&M LCoE Analysis Tool to provide an overarching cost of energy for generic projects within U.S. waters.

From this investigation, and based on the results presented in this Report, the following general conclusions can be drawn:

1. Novel installation methodologies that have reduced weather window constraints will need to be considered for the Pacific regions if economic offshore wind projects are to be realized in these locations. While the impact of the often harsh metocean climate is less on O&M costs, due to the ability to access the wind turbines using helicopters, novel access methodologies would have to be developed for far-shore projects (out of shore-based range) or where larger wind turbine components (which cannot be transported by helicopter) require replacement.
2. Consideration will also need to be given to the installation and O&M activities within the U.S. Great Lakes region, where winter icing prevents installation during winter months and novel, currently untested, O&M access methodologies will have to be considered. Of particular note during winter months, when the wind resource is at its peak, is the potential requirement for the change-out of larger wind turbine components that would require the attention of a jack-up vessel which would – at that time, be unable to access the wind farm site during icing conditions.
3. Based on the analysis performed as part of this study, it is concluded that costs savings associated with installation and O&M can be achieved through the use of fewer, larger wind turbines. While there are time penalties associated with the installation of larger components offshore, these are not normally directly proportional to the capacity of the wind turbine, therefore it is possible to achieve time and, consequently, cost savings by adopting larger wind turbines. However, it should be noted that when considering this conclusion in the context of O&M costs, GL GH has not taken into consideration any changes in the reliability of wind turbine components or the durations required for their repair/replacement.
4. While gravity base structures appear to provide savings in terms of installation duration and costs for some project locations and scenarios, the costs associated with the pre-installation storage of these foundations as well as the significant lead times associated with their fabrication need to be taken into consideration.
5. As expected, installation and O&M costs increase with the severity of a metocean climate. It is not uncommon for these costs to double in their projected contribution to a project's LCoE due to harsh conditions. This is true of changes in severity as the project is located further from the U.S. coast, but is also true as the project is located in different geographical regions around U.S. waters, with the Pacific Coastal region displaying extremely high installation and O&M costs due to harsh offshore conditions.

It should be noted that the above conclusions are a result of comparison against a single baseline case assessed using the Installation and O&M LCoE Analysis Tool. Changes in project characteristics or input costs may dramatically change the results provided by the tool and hence the results documented in this Report should be viewed as applicable only to the limited scenarios reviewed here.

The results presented as part of this Report are a subset of those available within the Installation and O&M LCoE Analysis Tool. The Installation and O&M LCoE Analysis Tool is intended to provide users with the ability to assess a much wider set of strategic scenarios as well as costs as individual requirements dictate.

1 INTRODUCTION

This report (the Report) forms part of Subtopic 5.3 "Optimized Installation, Operation and Maintenance Strategies Study" which in turn is part of the "Removing Market Barriers in U.S. Offshore Wind" Project for the U.S. Department of Energy (DOE). The purpose of this Subtopic is to aid and facilitate informed decision-making surrounding installation and operations and maintenance (O&M) during the development, installation, and operation of offshore wind projects.

Both installation and O&M activities at offshore wind projects require considerable logistics planning from an early stage in project development in order to ensure cost-effective project construction and operation and to inject associated design criteria into the development process. Some decisions associated with these critical activities are largely determined by the physical constraints of the project, such as soil conditions, water depth, and distance from port, while others are less limited and open to optimization by the developer, contractor or supplier to minimize costs and maximize revenue. Furthermore many strategic installation and O&M decisions are influenced by, and can influence, critical foundation, turbine, and electrical infrastructure design choices, such as foundation type, detailed component design and project layout.

To assist the U.S. Offshore Wind Industry and Supply Chain in addressing the substantial number of alternative factors associated with installation and O&M, the DOE has requested that GL Garrad Hassan (GL GH) investigate the logistics and costs associated with existing and emerging installation and O&M activities at offshore wind projects.

This request has been addressed through two deliverables:

1. This Report:

- Looks at the primary site conditions affecting installation and O&M in U.S. waters;
- Provides a summary of current and emerging installation and O&M equipment and methodologies;
- Shortlists these methodologies for modeling and further analysis;
- Describes the approach to the modeling and assumptions made;
- Details how the modeling is applied within the Installation and O&M LCoE Analysis Tool;
- Provides a user guide for the Installation and O&M LCoE Analysis Tool; and
- Derives a series of headline results from the modeling.

2. Installation and O&M LCoE Analysis Tool (701216-UKBR-01-XL-D):

- Provides functionality to review alternative regions, climates, and project configurations;
- Enables the analysis of a wide range of alternative current and emerging installation and O&M methodologies;
- Allows all unit cost assumptions to be reviewed and amended;
- Allows results to be reviewed in terms of Levelized Cost of Energy (LCoE) through the intrinsic estimation of energy yield within the tool; and
- Provides detailed cost and scheduling breakdowns allowing sensitivity studies and comparison of alternative strategies.

Ultimately, many of the strategic and design decisions affect both direct costs (capital expenditure (CapEx) and Operational Expenditure (OpEx)) and project performance, such as energy yield and availability. Therefore, Levelized Cost of Energy (LCoE) has been used within this study as the primary metric for evaluating installation and O&M methodologies as this approach inherently captures both direct costs and project performance and therefore reflects overall project economics. The Installation and O&M LCoE Analysis Tool, and its use, are described in further detail in Appendix A.

This Report and the associated Installation and O&M LCoE Analysis Tool are targeted at a wide range of stakeholders involved during the planning, construction, and operational phases of an offshore wind project, including:

- Developers;
- Turbine suppliers;
- Manufacturers;
- Installation contractors;
- Vessel owners and operators;
- Helicopter operators;
- Materials, parts, and consumables supply chain;
- Lifting equipment specialists;
- Specialist marine contractors;
- Investors and lenders; and
- All those interested in the technical, scheduling, and cost aspects associated with the installation and O&M of offshore wind projects.

Further, this Report is structured to reflect the order of approach to the overall study and follows the progression below:

1. Review of U.S. Site Conditions and Installation and O&M methodologies (Sections 2 – 4);
2. Analysis and synthesis of meteorological and oceanographic conditions (Section 5);
3. Shortlisting and modeling of the Installation and O&M activities (Sections 6 – 7);
4. Estimation of Annual Energy Production for LCoE calculation (Section 8);
5. Description of the methodology adopted for LCoE calculation (Section 9);
6. A brief selection of key results derived using the Installation and O&M LCoE Analysis Tool (Section 10); and
7. A User Guide for the Installation and O&M LCoE Analysis Tool (Appendix A)

An overview of the structure and flow of the study is illustrated in Figure 1-1 with section numbers relating to those in this Report.

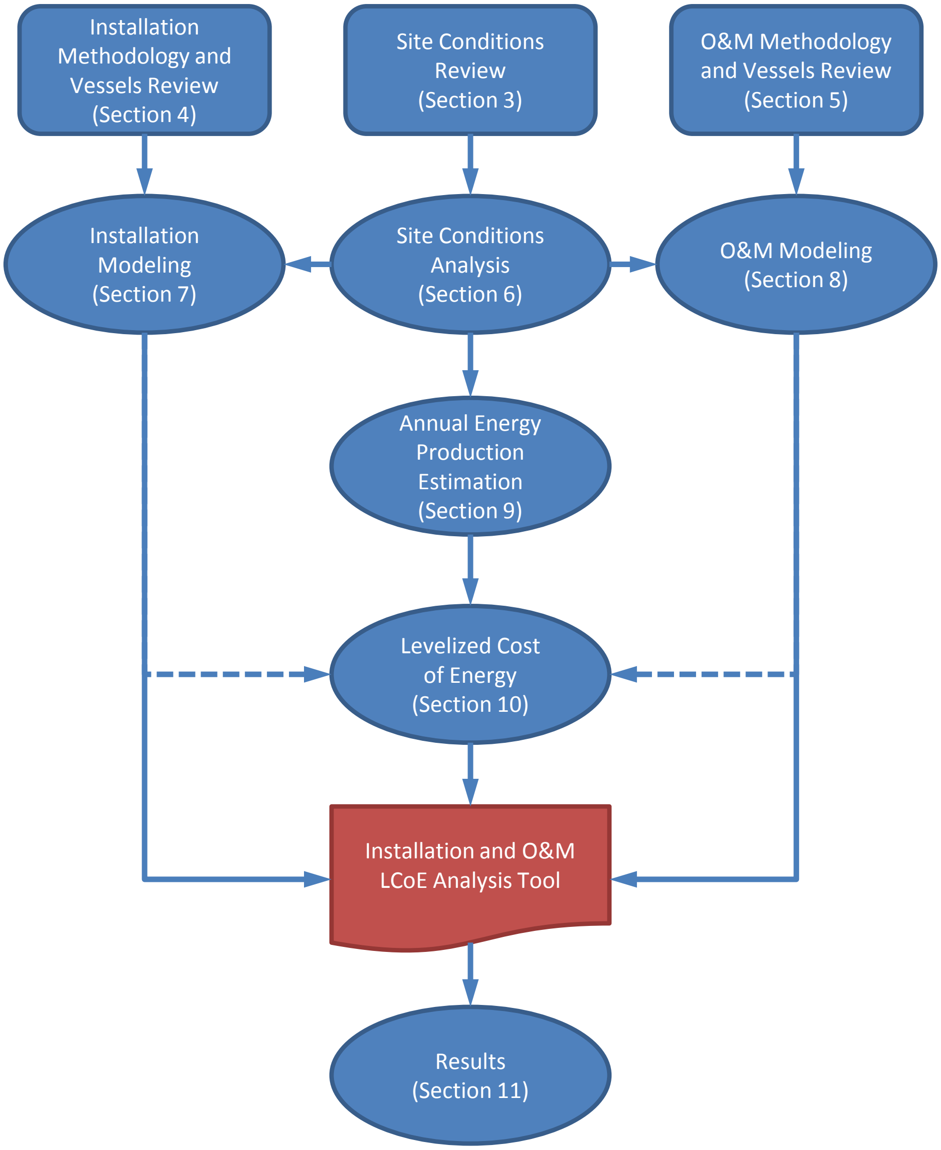


Figure 1-1: Structure of Subtopic 5.3 Analysis and Deliverables

Using this Report and the accompanying Installation and O&M LCoE Analysis Tool, readers shall be able to identify, model and probe the technical and economic merits and sensitivities of alternative approaches to installation and O&M at a wide range of alternative offshore projects located in U.S. waters.

2 SITE CONDITIONS REVIEW

2.1 U.S. Regional Distribution

The U.S. has considerable territorial waters in which an offshore wind energy industry could be established and developed to provide a substantial contribution towards the national target of 20% of wind energy by 2030. In order to assess the logistics and costs associated with installation and O&M activities required for deployment of offshore wind projects within the U.S., it is necessary to divide the country's waters into a series of zones for which average conditions may be identified.

To achieve this, GL GH has considered the regional distribution described in the recommendations of the Navigant report: "Recommended Approach to Offshore Capacity Deployment Scenarios" [2], wherein the U.S. coasts have been divided into 4 main regions:

1. Atlantic Coast;
2. Pacific Coast;
3. Gulf Coast; and
4. Great Lakes.

Due to the very large areas and wide ranging conditions encompassed within the four regions, these were further sub-divided into 8 sub-regions based on their geological and meteorological conditions as illustrated in Figure 2-1. The 8 sub-regions are:

1. Atlantic North;
2. Atlantic Central;
3. Atlantic South;
4. Gulf of Mexico East;
5. Gulf of Mexico West;
6. Pacific North;
7. Pacific South; and
8. Great Lakes.

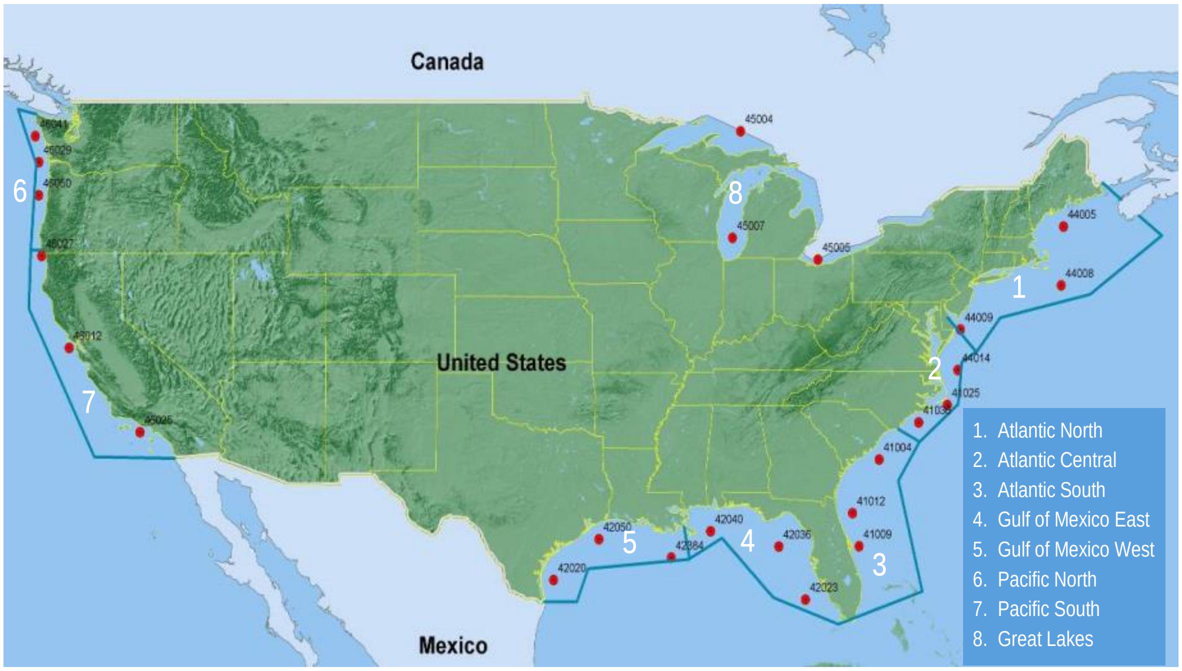


Figure 2-1: Division of U.S. Coastal Regions

Since each of the 8 sub-regions span a considerable area, it was considered unlikely that any single location would be representative of the meteorological and oceanographic (metocean) conditions across the associated region. Therefore, GL GH identified three alternative locations for each zone in an effort to capture a range of different climatic conditions. Wind speed and wave data time series were sourced at each of these locations. The geographical locations of these data measurement points are illustrated in Appendix C.

2.2 Metocean Conditions

In order to assess the meteorological and sea state conditions of each region, wind and significant wave height time series for the Atlantic Coast, Gulf Coast, and Pacific Coast were compiled from the National Oceanographic and Atmospheric Administration (NOAA) WAVEWATCH III hind cast model which uses operational National Centers for Environmental Protection (NCEP) products as inputs [3]. The dataset includes time series of significant wave height, wave direction, wind speed, and wind direction from 1 January 2001 to 31 December 2010. Data locations were selected to collate with existing National Data Buoy Center (NDBC) buoy stations [4] which will allow future inter-comparison between model data and measurement data (if required). Data for the Great Lakes region were derived from a combination of NDBC [4] wave buoy data and shore-based wind station data in Lake Michigan due to the removal of buoys during periods of ice coverage.

Geographic latitude and longitude, water depth, and long-term (11 years) average conditions for each NDBC buoy location are summarized in Table 2-1.

Table 2-1: Summary of NDBC Stations Used in this Study

Region		NDBC Station	Latitude [N]	Longitude [W]	Water Depth [m]	Average Significant Wave Height [m]	Average Wind Speed @ 10 m MSL [m/s]
Atlantic	North	44009	38.464	74.702	28	1.13	6.3
		44005	43.204	69.128	206	1.10	6.7
		44008	40.502	69.247	65	1.75	7.5
	Central	44014	36.611	74.842	95	1.58	7.4
		41025	35.006	75.402	68	1.70	7.7
		42036	28.500	84.517	54	0.66	5.4
	South	41004	32.501	79.099	38	1.20	6.5
		41009	28.523	80.184	40	1.38	6.5
		41012	30.042	80.534	38	1.25	5.6
Gulf of Mexico	West	42020	26.966	96.695	88	1.28	6.7
		42050	28.843	94.242	24	0.98	6.3
		42384	27.993	90.326	455	1.06	5.8
	East	41036	34.207	76.949	25	1.53	7.5
		42023	26.064	83.074	90	0.86	5.5
		42040	29.212	88.207	165	0.90	5.7
Pacific	North	46029	46.159	124.514	145	2.61	7.0
		46041	47.349	124.708	114	2.55	6.7
		46050	44.639	124.534	128	2.62	7.0
	South	46012	37.630	122.881	209	2.35	6.3
		46025	33.749	119.053	905	1.80	5.5
		46027	41.850	124.381	48	2.64	7.3
Great Lakes		45004	47.584	86.587	226	0.84	6.9
		45005	41.677	82.398	13	0.58	6.0
		45007	42.674	87.026	160	0.75	6.4

Subsequent processing of the time series data for the purposes of installation and O&M modeling is described in Section 5 of this Report.

2.3 Ice Coverage Conditions

Sea or lake ice is an important consideration for both O&M and installation activities and hence it is necessary to consider the historic frequency and duration of occurrence of ice in each region. Significant sea-ice coverage around the majority of the U.S. coasts is not anticipated, however, it is common for the Great Lakes to be covered by ice for 3-4 months of the year. For this reason, data from the NOAA Great Lakes Ices Atlas [5] were used to compile time series of daily ice coverage (expressed as percentages) from January 1973 to December 2002. These data are presented graphically in Appendix C.

Further processing of these data was required for the purposes of the installation and O&M modeling as described in Section 5.

2.4 Seabed Conditions

A brief summary of water depth, geological and seismic conditions anticipated in each region is summarized in Table 2-2.

Table 2-2: Geographical Characteristics of Each Region

Description	Atlantic Coast	Gulf Coast	Pacific Coast	Great Lakes
Average Water Depth [m]	Average depth of the Continental Shelf is ~100 m			Variable in each lake.
Average soil type[1]	Coastal: sand and gravel. Offshore: mud, clay and biogenic sediment.			Sand, clay, mud, silt.
Seabed type[1]	Location dependent (granite, shale, volcanic)			
Seismic Risks	Medium	Low	High	Medium

1. The soil and seabed description provided here is for general assessment only. The thickness, composition, formation of sediment, and strength of the bedrock can be very complex and may vary considerably from site to site.

Water depth is also an important criterion when considering the types of foundations which might be adopted in each region and the approach used to transport and install them. Table 2-3 shows the sea surface area with respect to binned water depths for each region based on bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO) data set. Note that regions deeper than 300 m have not been included as GL GH considers such depths to be economically unattractive for the deployment of offshore wind before 2030.

Table 2-3: Sea Surface Area vs. Water Depth for Each Region

Region		Surface Area with 0-10 m Depth [km^2]	Surface Area with 11-30 m Depth [km^2]	Surface Area with 31-50 m Depth [km^2]	Surface Area with 51-150 m Depth [km^2]	Surface Area with 151-300 m Depth [km^2]
Atlantic	North	7,531	22,918	33,861	82,131	44,641
	Central	18,927	29,175	16,477	11,069	2,274
	South	9,242	47,144	25,113	10,569	14,647
Gulf of Mexico	West	41,274	55,323	39,982	54,257	31,520
	East	23,105	44,150	25,671	38,768	9,694
Pacific	North	1,671	2,532	2,949	18,108	8,079
	South	1,607	3,358	3,446	16,974	7,167
Great Lakes		21,200	45,160	23,907	91,357	57,167

3 INSTALLATION METHODOLOGY AND VESSELS REVIEW

The installation of offshore wind projects can be carried out via a large variety of onshore and offshore procedures and activities. Clearly, many of these approaches will be governed by the nature and types of foundations, turbines and other plant to be installed. Further choices will be dependent upon the seabed and metocean climate conditions at the site. But even once these factors are understood and designs have been finalized, multiple logistical approaches are usually available to developers.

To date, many of the techniques, approaches and vessels employed can be traced back to other offshore industries, most notably the offshore oil and gas sector. However, with the recent rapid expansion in offshore wind internationally, the industry is now readily exploring new alternative options for installation, from minor improvements in handling and speed of operations to the production of purpose-built vessels and novel installation methodologies. Each approach has its merits and weaknesses, and places different demands upon the vessels, cranage, equipment, and components during the installation.

The purpose of this Section is to identify and review existing, emerging, and future vessels and methodologies for the installation phase of offshore wind projects. For the purposes of this study, installation has been assumed to include the following activities:

- Transportation of components to the offshore site;
- Installation of foundations and associated steelwork;
- Installation of offshore wind turbines and associated components;
- Installation of cables and electrical infrastructure;
- Commissioning of the turbines.

3.1 Introduction to Installation Considerations and Requirements

As part of this review, it is important to be aware of the primary areas of cost and risk during the installation phase of an offshore wind project. This sub-section provides a brief overview of those risks.

The majority of offshore construction costs are attributable to vessel day rates. Therefore, effort spent in seeking appropriate installation vessels and methodologies is critical and should aim to identify strategies with the best balance between vessel costs, activity duration, and perceived risk for delays. Marine contracts are very different from most of those encountered in onshore construction; the legal documents required to carry out marine transportation are discussed within this review.

Clearly, many offshore operations are limited by the weather conditions under which they can be safely conducted. Therefore the location of the project, the season during which each phase of installation is carried out and the vessel and installation methodology adopted for that phase of the work are likely to have a strong influence on the degree of accrued weather downtime. Whether the risk and cost of these weather downtime intervals are absorbed by the project developer or the installation contractor will depend largely upon the contractual agreements in place, but the costs due to inactivity can be substantial and will impact stakeholders at one level or another. It is therefore critical to carefully evaluate the anticipated site conditions (see Sections 2 and 5) as well as the limits placed upon each operation and vessel considered.

Other installation risks include vessel availability or delays, vessel and equipment failures, inadequate design or manufacture of components, and any delays from other aspects of the project, such as procurement, supply or consenting. Furthermore, many installation activities must be performed in sequence and hence it is important to minimize and mitigate delays which can accrue additional costs in later stages, especially on critical path activities.

Further factors which may affect the choice of installation operations are legal and consenting requirements at regional, national, and international levels. The international bodies that have jurisdiction over these offshore activities are therefore briefly introduced within this review.

3.2 Installation Methodologies

For the purposes of this review, installation has been assumed to cover all activities involved in getting the components required for an offshore wind project to the offshore site location and their subsequent installation and commissioning, including any seabed preparation and scour protection works. It therefore does not include the onshore fabrication of components or any pre-installation surveys, sampling or other site investigation or design works.

3.2.1 Introduction to Onshore and Offshore Cranes

Fundamental to the majority of installation methodologies and associated equipment are cranes and lifting operations. This sub-section provides a brief background to cranes, their safe-usage, and the associated terminology. Lifting tackle is subsequently discussed in Section 3.2.2.

Types of Crane

There are nine primary types of crane commonly used within the offshore wind industry that may need to be considered when planning onshore and offshore aspects of installation works. These are summarized briefly in Table 3-1.

Table 3-1: Generalized Types of Crane Commonly Used in Support of Offshore Wind Installation

Crane Type	Description	Example Image
Pedestal	An offshore-specialist crane configuration, which is mounted upon a steel columnar pedestal. The crane is designed such that the lifting loads are passed directly into the structure of the vessel, so a counter-weight is not required, and an overall lighter crane can be used. This reduced crane weight increases the available cargo and jacking capacity of the vessel upon which it is mounted. The boom has a high transverse stiffness to enable dynamic lifting from feeder barges and supply vessels.	 MPI Resolution. Source: GL GH
Round the Leg	On a jack-up vessel, to avoid taking up deck space, the crane can be mounted on a slewing ring fitting around one of the jack-legs. Much like a pedestal crane, this is an offshore-specified crane type with high transverse boom strength, suitable for dynamic lifting from feeder barges and supply vessels.	 Source: HGO Infrasea Solutions.
Knuckle-boom	A particular form of pedestal mounted crane with a boom which folds back on itself, allowing for a compact crane footprint. Often equipped with heave compensation, these cranes are preferred for light-to-medium duties on offshore supply vessels for loading and unloading, as well as light offshore construction duties.	 Source: GL GH

Crane Type	Description	Example Image
Sheerleg	Often in the form of a modified, unpowered (deck) barge which has an A-frame fitted to one end serving as a crane boom. The A-frame can generally be raised and lowered as required. Limited stability makes these cranes best suited to low-cost river, estuarine, and inshore heavy-lift requirements. The lack of any rotation or slewing of the crane results in limited maneuverability, requiring the entire vessel to be moved for transverse or longitudinal movement of the load.	 Source: Alpha Ventus
Crawler	An on-shore crane, with two tracks of wide load-spreading pads, for "pick-and-carry" duties, even in soft ground conditions. Crawler cranes usually feature an approximately square boom section providing some limited transverse strength for grab and dragline duties. Several hook-block options are available to optimize utilization. Booms typically comprise a head-and-tail section with modular inserts, often with fly-jibs for additional reach and additional "super-lift" counter-weights, with separate load radius charts for each boom configuration. With care, crawler cranes may also be used offshore on stable jack-up vessels for installation applications.	 Source: Sany Heavy Industry
Mobile	Road-legal, generally telescopic-boomed, highly optimized and light-weight lift-cranes. Generally equipped with four out-rigger legs which impart concentrated loads, requiring careful investigation of localized ground strength during lift planning. Easy mobilization but typically high day rates. Several hook-block options are available to optimize utilization. As with crawler cranes, these may also be used offshore on jack-up vessels for installation applications.	 Source: Liebherr, windpowerengineering

Crane Type	Description	Example Image
Ringer	An attachment for increasing the lift capacity of a crawler crane by mounting the boom on a circular rail called the “ring”, and mounting a larger counterweight diametrically opposite the boom on the back of the ring. A rear boom transmits the load into the counterweight, increasing lift-capacity. Otherwise this arrangement is similar to that of a crawler crane, but without the ability to transport loads over distances greater than the boom radius and slewing allow.	 Mantiwoc Ringer. Source: Andekan
Harbor Crane	Generally multi-wheel trailer, or rail mounted cranes with a high level cab, (to allow good views into the holds of un-laden vessels), these are light-duty (~200t max) lattice-boom specialist rapid-hoist, cyclic-duty loading and unloading cranes. A load spreading under-carriage is vital to allow operation on quaysides, distributing lift-loads as widely as possible, to avoid overloading quay-wall piling. Harbor cranes can be operated in tandem-lift configurations to achieve ~400t maximum capacity, which allows all blade types, most tower sections and even the largest nacelles to be handled, but some foundations will require heavier lift capacities.	 Source: Liebherr
Gantry	Generally an onshore crane, in which a horizontal beam is supported at two points along its length by two A-frames which are in-turn often rail-mounted. This arrangement provides useful longitudinal and transverse load-carrying capabilities, sometimes on a large scale. One or more trolley-mounted winch-units hang from the cross beam, and sometimes multiple gantries are mounted on a single pair of rails affording tandem lifting configurations for large objects. Widely used for storage yards, shipyards and occasionally spanning load-out basins or dry-docks to facilitate the lifting of heavy-loads between land and vessels.	 Harland and Wolff. Source: GL GH

General Crane Specifications

A brief description of the basic components and specifications of cranes is provided in Figure 3-1 and the proceeding text.

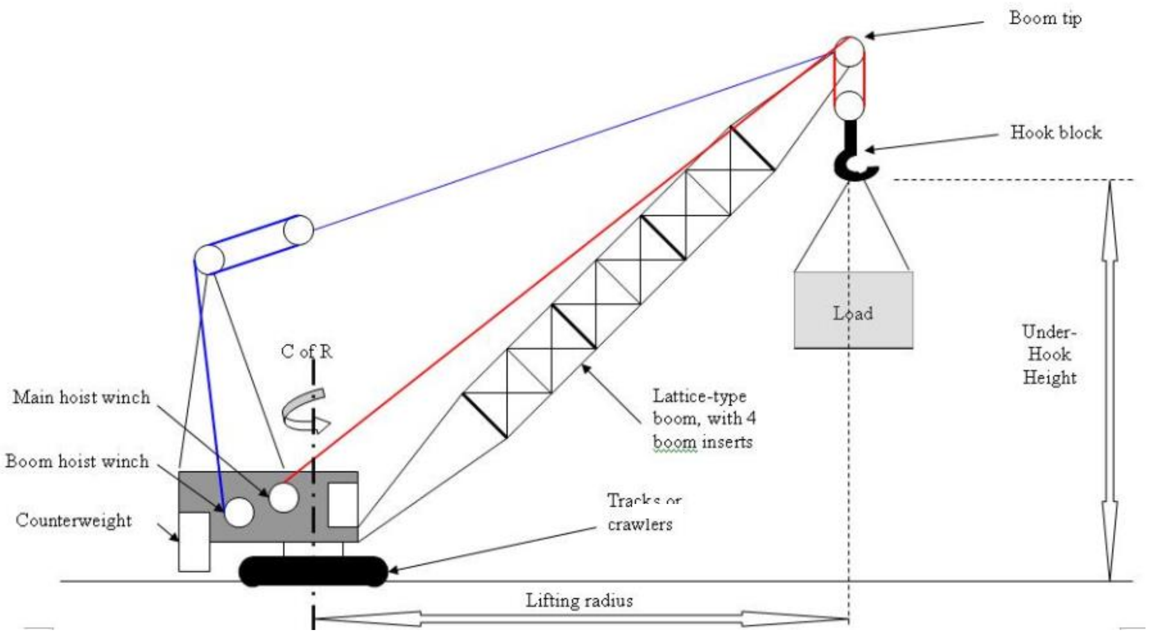


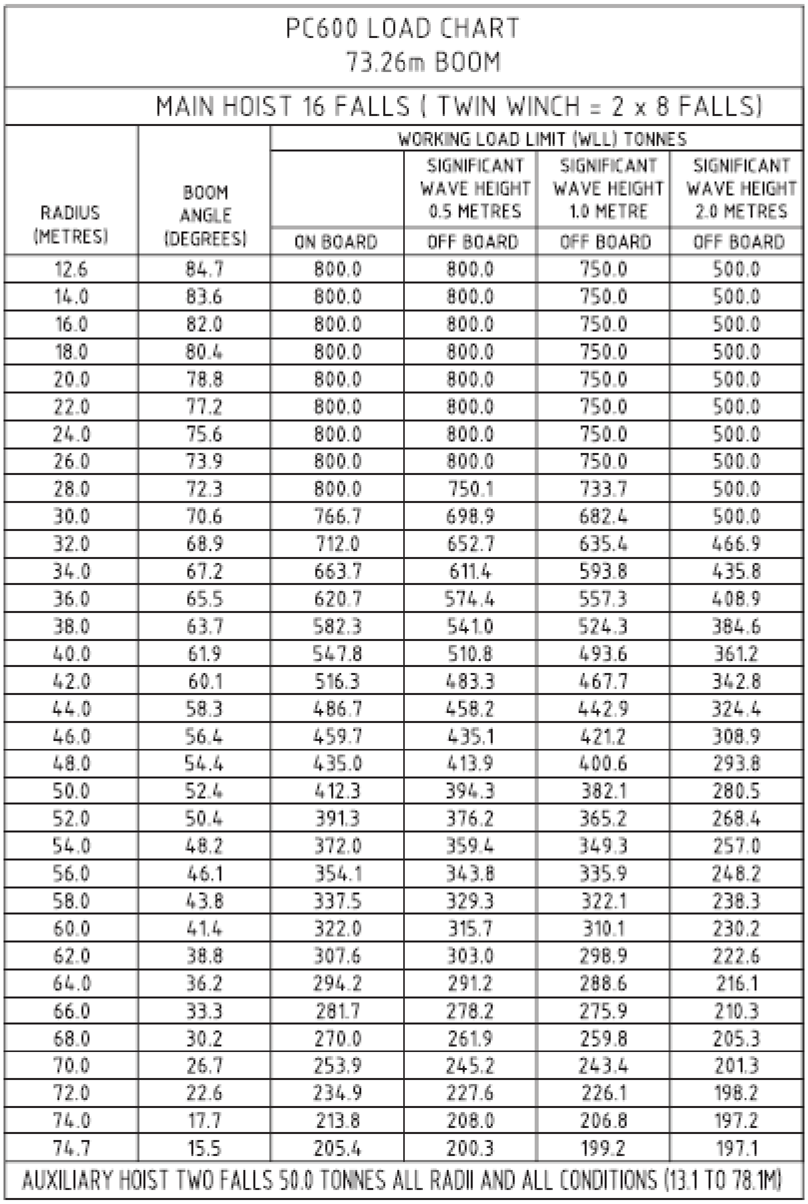
Figure 3-1: Crawler Crane, Showing Key Components and Dimensions

Clearly, cranes must have the appropriate specifications for each particular lifting operation, with primary particulars including:

- Under-hook height (including all necessary lifting tackle);
- Space for load without striking boom at all required boom heights;
- Lifting radius;
- Safe working load (SWL), based on:
  - Maximum boom radius during lift;
  - Onshore or offshore lift; and
  - Significant wave height (affects minimum rate of lifting).

Crane manufacturers publish specifications of their equipment with the most important information within this being the tabular performance sheet, detailing what load can be safely lifted at each particular lifting radius.

Table 3-2: Example of an Offshore Crane Load Radius Table



PC600 LOAD CHART
73.26m BOOM

MAIN HOIST 16 FALLS (TWIN WINCH = 2 x 8 FALLS)

RADIUS (METRES)	BOOM ANGLE (DEGREES)	WORKING LOAD LIMIT (WLL) TONNES			
			SIGNIFICANT WAVE HEIGHT 0.5 METRES	SIGNIFICANT WAVE HEIGHT 1.0 METRE	SIGNIFICANT WAVE HEIGHT 2.0 METRES
		ON BOARD	OFF BOARD	OFF BOARD	OFF BOARD
12.6	84.7	800.0	800.0	750.0	500.0
14.0	83.6	800.0	800.0	750.0	500.0
16.0	82.0	800.0	800.0	750.0	500.0
18.0	80.4	800.0	800.0	750.0	500.0
20.0	78.8	800.0	800.0	750.0	500.0
22.0	77.2	800.0	800.0	750.0	500.0
24.0	75.6	800.0	800.0	750.0	500.0
26.0	73.9	800.0	800.0	750.0	500.0
28.0	72.3	800.0	750.1	733.7	500.0
30.0	70.6	766.7	698.9	682.4	500.0
32.0	68.9	712.0	652.7	635.4	466.9
34.0	67.2	663.7	611.4	593.8	435.8
36.0	65.5	620.7	574.4	557.3	408.9
38.0	63.7	582.3	541.0	524.3	384.6
40.0	61.9	547.8	510.8	493.6	361.2
42.0	60.1	516.3	483.3	467.7	342.8
44.0	58.3	486.7	458.2	442.9	324.4
46.0	56.4	459.7	435.1	421.2	308.9
48.0	54.4	435.0	413.9	400.6	293.8
50.0	52.4	412.3	394.3	382.1	280.5
52.0	50.4	391.3	376.2	365.2	268.4
54.0	48.2	372.0	359.4	349.3	257.0
56.0	46.1	354.1	343.8	335.9	248.2
58.0	43.8	337.5	329.3	322.1	238.3
60.0	41.4	322.0	315.7	310.1	230.2
62.0	38.8	307.6	303.0	298.9	222.6
64.0	36.2	294.2	291.2	288.6	216.1
66.0	33.3	281.7	278.2	275.9	210.3
68.0	30.2	270.0	261.9	259.8	205.3
70.0	26.7	253.9	245.2	243.4	201.3
72.0	22.6	234.9	227.6	226.1	198.2
74.0	17.7	213.8	208.0	206.8	197.2
74.7	15.5	205.4	200.3	199.2	197.1

AUXILIARY HOIST TWO FALLS 50.0 TONNES ALL RADII AND ALL CONDITIONS (13.1 TO 78.1M)

Source: Favell Favco cranes

When performing dynamic lifts offshore (termed “off board” in Table 2-2), winch line speeds are a further factor. When lifting onshore, or from a jack-up to a turbine foundation, this is not normally a problem, as little differential motion exists between the load and crane. However, when lifting a load from a deck on a barge which is rising and falling with successive waves, winch speeds have significant implications. If the load’s vertical acceleration is insufficient to exceed any subsequent vertical, wave-induced movements of the deck, the load may hit the deck. Not only can this cause damage to both the load and barge, but a snatch load will also be applied to the crane, potentially exceeding operational limits. For this reason, when planning offshore lifts, it is vital to consider not only the load and its radius, but also the maximum rate at which the load may be hoisted (dependent upon both the winch line speed and the reeving configuration between the boom tip and hook block).

A differentiating factor for floating offshore lifts is the lateral capacity of the crane boom. Most crane booms designed for onshore use have relatively low lateral strengths in comparison with their vertical lift capacity. Offshore, however, lateral movements of the load due to vessel heave can incur significant horizontal components to the load paths. As a result, cranes used in dynamic situations, such as on the deck of a floating vessel, are either specifically designed for increased lateral loads or may be down-rated from their maximum onshore, static lift capacity. This can have significant implications when using crawler or other onshore cranes on an offshore vessel.

Another key dimension of the crane's specifications to consider when planning lifts is the under-hook height. With turbine components lifted to ever increasing heights, it becomes more important to study closely whether the crane can accommodate both the required height of the load and that of any lifting tackle (see Section 3.2.2).

It is also necessary to consider the shape of the lifted load and to consider whether, once it is hanging from the hook, the load will fit in the space between the boom and the crane hook. When lifting a blade, rotor, or nacelle, the boom is lifted to a high angle of elevation, often leaving quite a small distance between the boom and hook block. Clearly there is a danger that any movement of the load will impact the boom, damaging the boom and hook block.

3.2.2 Loading and Un-Loading

Before assessing the vessels and offshore methodologies required to carry out the transportation and installation of wind turbines, it is necessary to have a thorough appreciation of the primary methods by which components are handled onshore.

Historically, wind turbines were manufactured with onshore installation in mind. The remoteness of many onshore project sites was a key driver in determining maximum component sizes and their design for largely road-based transport. Nevertheless, the international scale of the wind turbine market led to the location of many turbine manufacturers on or near coastal, river or estuarine port facilities, placing them in a favorable position for the subsequent offshore wind market.

The increased size of offshore turbines can restrict many traditional approaches to road-based transport of components. However, it is normal practice for components to be transported by sea directly from the manufacturer to a marshaling or mobilization port, before subsequent transport to the offshore site, thus avoiding any significant onshore transport with the exception of general port logistics. In some cases, turbines may even be shipped directly to site from the manufacturer port facility, limiting onshore handling still further.

Foundations and other offshore components have, by necessity, followed a similar route, with fabricators and suppliers largely based in close proximity to a suitable port. Once again a marshaling or mobilization port may be adopted as an interim storage facility, depending largely on the transit distance between the site and the fabrication port.

There are various alternative transportation procedures for moving turbines and foundations from the manufacturer's premises to the offshore wind farm site. The generally applicable alternatives are:

- Loading of components at the manufacturer's port facility. Offloading them onto quayside storage areas at the marshaling port to be collected by a feeder vessel or installation vessel as required on site; or

- Loading of components onto a transport vessel or barge at the manufacturer's premises and either anchoring the transport barge or offloading onto a floating barge in a sheltered harbor near the offshore wind farm site, to be stored, awaiting transfer to the installation vessel; or
- Loading of components onto a transport vessel or barge at the manufacturer's premises, and offloading onto the installation craft at the offshore wind farm site – known as feeder vessel duties; or
- Loading of components directly onto the installation craft at the manufacturer's premises, and subsequent installation at the offshore wind farm site.

The loading of the vessels in ports can be performed in a variety of ways, but currently the most common approaches are the lifting and rolling of components onto the deck or into the holds of the vessel, using techniques known as RoRo and LoLo, respectively. The term RoRo is an abbreviation of the descriptive term: "Roll-on, Roll-off", while LoLo is an abbreviation of "Lift-On, Lift-Off". Both have significant implications, with regard to vessels, port infrastructure, and mechanical plant selection. The practicalities and implications of both techniques will be thoroughly reviewed in the following sections.

For completeness, other techniques include rollers, grease and air skates, crawler transport units and skidding techniques, all of which are all technically possible, but are generally less favored within the industry.

RoRo

RoRo is most commonly associated with passenger car ferries, where both commercial vehicles and private cars are loaded and unloaded onto the vessel by driving on and off ramps, using a customized port access device called a link-span.

Source: GL GH

Figure 3-2: RoRo Ferry Berthed Aft-on to a Link-span

Many onshore wind turbine components are transported using RoRo ferries, when they are not operating to a commercial timetable. The larger offshore turbines are unlikely to be transported using ferries, as their components are generally larger than even the largest freight transport for which the ferries and link-spans are designed; they are also too large to be road-hauled via infrastructure designed for similarly-sized vehicles. However, this methodology is applicable to loading and unloading turbine components which are transported by barge, and some cargo vessels have decks which can be used for RoRo cargos.

In order to determine whether a particular link-span can be used with a particular barge or vessel, and under what particular circumstances, i.e. in terms of ballasting, state of the tide, around timetabled usage of the RoRo, etc., a separate study by a specialist project cargo freight-forwarding specialist would be required.

Permanent Port Infrastructure and the Mobile RoRo Berth

While some ports do not have permanent RoRo berths, it is possible to accommodate this facility by using a mobile RoRo ramp. This is a highly specialized piece of equipment, as it enables extension of a port's capability beyond that of its fixed infrastructure. Therefore, when reading the table of ports, the number of RoRo berths, and the category of cargo they are capable of carrying, this capability must be borne in mind.

There are some general cargo vessels and heavy-lift cargo vessels which have aft and/or bow ramps designed for RoRo cargos. Some vessels are designed with reinforced decks, and will only accommodate the RoRo cargos as deck loads, while others have more elaborate arrangements for accommodating the cargo below deck.

Source: Huismann Crane website [6]

Figure 3-3: RoRo Capable Heavy Lift Cargo Vessel – *Happy Buccaneer*

Self-Propelled Modular Transporters

Some wind farms have managed to avoid the need for heavy cranage by loading turbines and foundation components onto Self-Propelled Modular Transporters (SPMT), and by utilizing RoRo ship-type vessels or transport barges loaded from RoRo link-spans. Common forms of SPMT have individual two-axle units with a load carrying capability of ~30t / axle, and can be arranged side-by-side or end-to-end in a rolling transporter for extremely large loads.

Source: GL GH

Figure 3-4: Self-propelled Modular Transporters

Whether this type of unloading arrangement will be possible will be specific to each port facility and vessel combination, as gentle gradients and turning radii as well as sufficient headroom are required (often not available in existing port RoRo facilities).

Specialist heavy transport firms, or project cargo forwarders, can support companies wishing to investigate the suitability of individual port facilities for accepting specific cargos. However, each combination of vessel, port, and component will require individual assessment. If large numbers of components require storage, further assessment of the deck strengths or axle loads of haul routes between the RoRo offloading and storage areas will be required.

Any usage of incorporated roads would require that transportation complies with road haulage regulations for that part of the haulage route.

Despite the complexities of this transport method, it avoids the need for cranage, which can result in significant savings. Additional cost may however be incurred due to the need for storage frames or equivalent, which allows SPMTs to roll underneath and jack the load on and off.

LoLo

The term LoLo is an abbreviation of the descriptive term “Lift-on and Lift-off”. LoLo has traditionally been the most common way to load ships, and port facilities will often have cranage designed to accommodate the most common types of cargo passing through (although potentially not the demands of the offshore wind industry).
Lifting operations within port may be carried out either by land-based cranes on the quayside or by the use of the vessel cranage, if present.

Quayside Cranes

The types of freight which are commonly loaded on and off ships using cranes within port facilities vary dramatically and require very different lifting solutions:

- **Bulk and Granular Material:** Some bulk material cargos require cranes with grabber arms, while some ships may have internal hoppers and conveyor discharge systems built in. These types of arrangements are suitable for rocks, aggregates, other granular minerals (like grain), traditional solid fuels (like coal) and, increasingly, for wood-chips and pellets for biomass heating systems. Cranes dedicated to this application tend to be highly specialized, with relatively light lift capacities, but fast cycling capability (both hoist speeds and slew-rates). These would be unsuitable for lifting heavy turbine or foundation components, but may prove beneficial for loading or unloading rock, gravel, and grout materials during seabed preparation works, grouting works and burial or scour-protection works.
- **Containerized Freight:** Most “transit” cargos pass inland, through ports, and are therefore “packaged” in such a way as to be suitable for forwarding as either road or rail freight. The most common example of these is container shipping, which has dedicated vessels and port cranes, most of which are generally inappropriate for offshore wind installation purposes due to their relatively light lift capabilities and bespoke configuration.
- **Specialist and Non-containerized Cargo:** Mostly only located at ports serving large component fabricators, ship builders or other heavy industries, large harbor or gantry cranes are generally the most appropriate permanent quayside cranes for the purposes of offshore foundation and turbine loading and unloading. Ports which do not have such permanent specialist heavy-lift cranage may, however, utilize large mobile, crawler or ringer cranes given sufficient quayside bearing strengths. One valuable feature of a crawler crane, as opposed to mobile or ringer cranes, is its ability to pick a load up and to track forward, thereby transporting the load while suspended, an operation which is called “pick and carry”. This enables the use of a single crawler crane both to load and to transport turbine components around a marshaling yard, and avoids the additional expense of SPMTs. The cost penalty is that the transit speed of a laden crawler crane is extremely slow; therefore, any additional time requirement for chartering delivery vessels, and any associated equipment and personnel, will be greatly increased, but it may be cost-effective if travel distances can be kept to a minimum.

Many areas adjacent to quays have had rails fitted for tower or gantry cranes, which are no longer in regular use due largely to the increase in containerized freight. Generally these cranes are too small to meet the requirements of offshore installation, but the reinforced concrete beams along which the rails run, are often well supported by piles and may well have useful load bearing capacity, either for lifting or as haulage routes.

Vessel Cranes for Loading and Unloading

A common solution to loading and unloading wind turbine components in port is to use the onboard vessel cranage. Clearly this will require adequate onshore transportation facilities (such as SPMTs) and quayside bearing strengths to allow components to be located close enough to the vessel to fall within the crane radius.

Vessel cranes are not limited to installation vessels, but may also feature on large cargo vessels if used to transport components between manufacturers and marshaling ports. Figure 3-5 shows two pedestal cranes on a heavy lift cargo vessel used for the transportation and installation of transition pieces at the Greater Gabbard Offshore Wind Project in the UK. As with other cranes, these vessel-mounted cranes may be used in tandem to increase the overall lifting capacity.

Source: Offshorewind.biz

Figure 3-5: Pedestal Cranes on Jumbo Shipping's *Jumbo Javelin* Used to Install Transition Pieces at the Greater Gabbard Offshore Project

Independent Floating Cranage

Another option, in order to avoid having to use either a vessel fitted with its own crane or land-based cranage, is to use an independent floating crane. There are often lifting requirements in ports where the cranage is inadequate, and a large number of ports have floating cranes available to carry out these unusual, intermittent lifts.

One type of floating crane that is ideally suited to heavy lifting is the sheerleg crane. In its simplest form, it is effectively an unpowered (often termed "deck") barge, with a structural steel frame protruding over the forward edge and some form of lifting winch and pulley system (see Table 3-1).

Reducing Reliance on RoRo and LoLo

The requirement for RoRo and LoLo may be reduced by seeking alternatives to quayside storage and handling. If the foundation or turbine manufacturing facilities are nearby to the offshore site, then significant cost savings may be achieved by transiting directly between the manufacturer facilities and the site, without the use of a separate marshaling port, assuming sufficient capacity at the manufacturer facility to ensure a reasonable buffer of stock to make certain that production delays do not impact the installation schedule.

If, however, the offshore site is located a significant distance from either foundation or turbine manufacturing facilities, then an intermediate storage location is likely to be the more cost-efficient approach. This typically takes the form of a marshaling port, wherein sufficient quayside space, cranage and lay-down area is available for adequate buffering of components during installation. However, floating storage on low-cost, deck barges in a sheltered harbor is also an option for foundation and potentially some turbine components. This methodology avoids landing components, and could result in significant savings on port costs. Clearly, purchasing or chartering the deck barge for the duration of the work will need to be balanced against any such savings.

3.2.3 Lifting Frames and Sea Fastenings

Many components will require specialist lifting tackle in order to ensure safe and efficient lifting operations both onshore and offshore. A common example is that of a spreader bar, which is used to accommodate the horizontal loading which stems from lifting an object by multiple attachment points from a single crane hook. Without a spreader bar, some components would fail during the lift due to the horizontal component of force within the lifting strops between the component and the crane hook. By implementing a spreader bar, these horizontal forces are opposed by the spreader bar, leaving only vertical loadings at the component lifting points. An example spreader bar is given in Figure 3-6.

Source: Global Project Logistics Network

Figure 3-6: Spreader Bar for a Nacelle Lift Operation

A further requirement for the offshore transportation of many components is a specialist support frame and sea-fastenings. The nature of these devices will depend heavily upon the specific design of the components, the deck layout of the vessel and the proposed installation methodology. Support frames commonly double-up as sea-fastenings with standard attachments used to connect these to the vessel deck, such as the twist-locks used in container shipping. Support frames may also act as lifting tackle in some cases, limiting the number of additional devices required as well as saving time changing lifting arrangements between lift operations. An example of support frames used for stacking and transporting turbine blades is provided in Figure 3-7.

Source: Global Project Logistics Network

Figure 3-7: Modular Support Frames Used for Stacking and Sea-Fastening of Turbine Blades

Unlike turbine components, foundations come in a variety of very different concepts and, even for a given concept, may vary considerably in terms of design and dimensions. Furthermore, it is common for foundations to vary to some extent even within a given project as water depths and ground conditions across the site dictate. This has led to a bespoke approach to the associated lifting tackle and sea-fastenings used with regard to foundations, with detailed solutions typically engineered on a project-specific basis. Some of the more commonly seen lifting tackle solutions are discussed as part of the installation methodologies reviewed in Section 3.2.5.

The following sub-sections discuss common lifting tackle and sea-fastening requirements of standard wind turbine components.

Tower

The tower is clearly vertical when fitted, and, rather than engage in complex offshore up-ending operations during the final installation, it is normal for the tower to be transferred to the offshore site in an upright position. The upper flange of each tower section has bolted connections, which are designed to take the considerable thrust loads induced by the turbines once operational, so these flanges form ideal points for locating lifting attachments. The latter are usually fitted to the tower sections before being loaded onto the deck of the installation barge and left in place; they are only removed once the tower has been installed in position, whereupon they are stored in preparation for the next batch of towers.

The towers are heavy and long and, combined with the rolling movements of a vessel, are capable of exerting significant loads on the transport vessel's deck. Typically these structures are either too heavy for the vessel crane to lift or pose too many obstructions to crane movement on deck when in one piece; hence transportation and subsequent installation in smaller sections is usually necessary (typically two parts). Furthermore, it may not be economical to design, fabricate, and secure deck frames substantial enough to react to the considerable loads which sea transits of whole vertical towers could inflict upon the deck.

Nacelle

The nacelle is usually transported on a structural steelwork frame. The upper fitments of this transport frame are designed to mimic the tower-top flange, while the underside is designed to interface with the mode(s) of transport that the nacelle will experience on its journey to the site.

The sea-lashing frame may also form a lifting cradle, to which lifting tackle, on a custom spreader beam arrangement, attach for swift lifting during loading and unloading in port. This optional functionality may add considerable weight to the frame, and it may be preferable simply to attach lifting tackle to the upper structure of the nacelle and “hang” a light-weight transport frame from the lower flange.

The nacelles are pre-assembled before offshore transportation, thereby minimizing the requirement for internal offshore assembly.

Blades

Various specialist spreader beams have been devised for turbine blades. Long lattice-type spreader beams would offer the lightest solution, but the more robust modular tubular devices have tended to be favored. During turbine installation, turbine manufacturers tend to use bespoke lifting frames to grip the blade at center of gravity (CoG) and tugger wires to control vertical and horizontal orientation (see Figure 3-8).

Source: Liftra

Figure 3-8: Turbine Blade Spreader Beam (yoke)

For complete rotor lifts, alternative lifting frames may be built to enable the rotation of the rotor from horizontal to vertical as the lift operation is performed. The rotation is typically performed using a second “house-keeping” crane to ensure the rotor is supported well above the ground or vessel deck throughout the lift.

Hub

The installation methodology will usually dictate whether the hub (or spinner) is transported pre-attached to the nacelle, or on its own transport frame. There are clear offshore assembly time savings to be gained if the hub is transported pre-fitted to the nacelle. However, the weight of the combined components may exceed the crane capacity.

Furthermore, if it is possible to fit the hub to the nacelle prior to installation, further offshore time savings are possible by ensuring that the hub is already aligned to accept the first blade (typically either horizontal or vertical).

However, a number of turbines, most notably the larger machines, have been designed to have the whole rotor (hub and three blades) pre-assembled before installation and then lifted onto the nacelle in situ. This operation can either be performed by transporting the hub and blades separately, and assembly of the rotor on the deck just prior to installation, or by loading the pre-assembled rotor. Many installation vessels have at least two cranes, and there is often time available, while the main crane is carrying out the two tower lifts and the nacelle lift, for the rotor to be assembled by another crane, deck space, and layout permitting.

An assembled rotor is a very bulky object in comparison to other turbine components and, to date, a maximum of just one or two assembled rotors per journey has been achieved by installation vessels, compared with 5-10 per journey when transported as separate blades in racked frames. To reduce the time the installation vessel spends journeying to and from site, feeder vessels are sometimes adopted to transport these bulky items to site while the installation vessel is engaged in lifting or repositioning operations. However, this is likely to add increased weather and equipment limitations to the turbine installation due to the requirement for dynamic offshore lifting between the feeder vessel and jack-up vessel.

To date, whole rotors have been transported to the offshore site oriented with the hub axis vertical and blades typically extending well beyond the outer dimensions of the vessel, requiring sizeable access routes to port facilities. If a second rotor is transported, this is usually located directly above the first with a bespoke frame used to support the hub and maintain the second rotor well above the first during transit. This approach requires specialist hub lifting equipment due to the needs for a 90° rotation during the lift to interface with the turbine nacelle. While this is a complex lifting procedure, it has been carried out successfully by multiple large offshore turbine manufacturers in continental Europe and the UK.

3.2.4 Offshore Transportation

There are various vessels which are commonly used to transport turbine components either between manufacturing facilities and marshaling ports or from either of these to the offshore site. Each type of vessel has its associated strengths and weaknesses, and these must be understood before appropriate vessel selections can be made for a given project. Furthermore, there may be alternative delivery and ports strategies available to the developer; for example, it may not always be cost effective to use a marshaling yard in a port close to the wind farm.

Some of the cost-benefit analysis underpinning these decisions will be based on the number of foundations or turbine components that can be transported during each voyage, which in turn shall depend upon the size and requirements of those components, deck layouts, strengths of various key areas of the decks and holds and the lift radii of any on-board, quayside and floating cranes used to load and unload vessels. Other factors will include the transit distances involved, the type of foundations and turbines and associated installation methodologies and the capabilities and restrictions of nearby ports or channels.

This section discusses some of the considerations when transporting foundations, wind turbines and other offshore components.

Periodic Motions of Floating Vessels

A brief comment on the physics of floating stability may provide an insight into the selection process undertaken by installation contractors for offshore lifts. The majority of the motion of floating vessels is composed of rotation about their longitudinal and transverse axes, termed rolling and pitching, respectively. The motion is induced by external forces, mostly waves and wind, or, in extreme cases, movement of ballast or cargo within the hold. Meanwhile, motion is countered by the buoyancy of the vessel.

A key design objective for any vessel is to ensure that the natural periods of these motions in any axis do not coincide with peak energy periods from waves since, from the general principles of dynamics, the greater the separation between the wave and vessel periods, the less the vessel motion response.

With very large, semi-submersible crane barges, the property of the vessel's period of roll is exploited by ballasting the vessel until its weight causes the associated period of roll to exceed the ambient wave periods. It is then highly stable and relatively unaffected by the wave conditions. Of course, any floating crane barge will be affected to some extent by wind and wave conditions and therefore some movement of the crane boom tip is inevitable. Boom tip motion is amplified when the tip is far removed from the center of rotation of the vessel, as it is with the high lifts required for wind turbine installation. The nacelle and blades lifts are therefore always carried out by a crane fitted to a jack-up vessel.

Transportation Vessels

The main types of vessels used for transportation of foundations and turbine components are briefly described in Table 3-3. Some of these vessels are used as feeder vessels only, transporting components to the site, but if properly equipped with lifting systems, they could also be used for some installation activities.

Table 3-3: Types of Vessels Used for Transport of Components on Offshore Wind Farms

Vessel Type	Description	Example Image
Floating Deck Barge	This is the most common type of vessel used to support river, coastal and estuarine marine construction projects. Deck barges are long, large, typically flat bottom vessels with no propulsion equipment. Often used for feeder vessel duties and potentially for ferrying components from the manufacturing port to the marshaling port due to the large, relatively uncluttered deck space. For the purposes of installation, a low-cost, floating lift-craft solution is formed by placing a land-based crane onto a deck barge for the purposes of low-height installations such as piling and foundation installation. Note that the deck barge in the example image also has spud-legs fitted for added stability and station keeping.	 Source: GL GH, Gunfleet Sands Wind Farm Deck Barge With Spud-Legs and Crawler Crane
Sheerleg Crane Barge	The sheerleg barge is fundamentally a very heavy-lift configuration of deck barge. The lifting frame fitted to the deck is permanent, and hence, to enable maneuverability, there is usually some form of skid-mounted or containerized propulsion unit fitted to the stern. The lack of slewing of the crane, as well as the considerable additional steelwork and equipment required to support the crane, typically limits carrying capacity to one component (e.g. foundation or pre-assembled turbine) suspended from the crane.	 Source: Alpha Ventus Sheerleg Crane vessel *Taklift 4*

Vessel Type	Description	Example Image
Semi-Submersible Heavy Lift Vessel	This type of vessel has been developed by the oil and gas industry to carry out placement of oil rig modules in harsh offshore conditions. The hull can be flooded, greatly increasing the deadweight of the craft, and it is designed so that this ballasting operation dramatically lowers the period of roll of the craft. Due to their considerable size, draft and cost, these vessels are never used solely for transportation purposes, but may transport large components to site, prior to their subsequent installation by the same vessel.	 Source: Alpha Ventus website Semi-submersible Heavy Lift Vessel *Thialf*
DP2 Heavy Lift Cargo Vessel	Cargo vessels deliver loads rapidly and cheaply around the world, and with the addition of heavy cranes, they can collect and deliver cargo from ports without adequate quayside crane capacity to handle the cargo. Within the hold these vessels usually have multiple bulkheads along their length and hence long cargos such as piles or blades are often stowed above deck level. Commonly used for port-to-port transport of large components or, when fitted with dynamic positioning, for feeder and occasionally installation duties using the onboard cranes for low-level lifts of foundation components, etc.	 Source: Jumbo Shipping website DP Heavy Lift Cargo Vessel *Jumbo Javelin*

Vessel Type	Description	Example Image
Leg-Stabilized Crane Vessel	To date only two vessels of this class have entered the wind farm installation fleet and both are owned by A2SEA – Sea Energy and Sea Power. Both were standard ships before they were retro-fitted with legs, and pedestal-mounted crawler cranes in 400t lift-configurations. These vessels use the legs to add stability and station keeping, but do not jack up fully out of the water. Nevertheless, this has proven sufficient in the past to perform high-level nacelle or rotor installation.	 Source: A2Sea Leg-Stabilized Crane Vessel A2Sea *Sea Power*
Self-Propelled or Towed Jack-up Barge	This type of vessel has been in use in the marine construction and offshore oil and gas industries for many years. The towed jack-up (or self-elevating platform, SEP) is a deck barge retro-fitted with jack-legs. Many are fitted with permanent cranes, but since they were designed to be customized for each new site, the existing crane can be upgraded, within the limits of the leg-jacking capacity. However, a new generation of self-propelled jack-up vessels, fully customized for offshore wind turbine installation activities, is now reaching the European market with a few of these "Offshore Wind Turbine Installation Vessels", such as the MPI "Resolution", now well experienced within the market. These vessels may be used for transportation of components to site as well as for their subsequent installation in a direct delivery and installation strategy.	 Source: GL GH Towed Jack Up Barge *Odin*

Delivery of Turbine Components from the Manufacturer to a Marshaling Yard

Most commonly, turbines are taken from the manufacturer's premises to a marshaling yard to avoid the use of costly installation vessels transiting over long distances. Each site is different and the turbine installation program will dictate how many turbines will require storage at any given time, but considering slippages, the area required to accommodate this number of turbines, and all the associated storage frames, can be calculated. This methodology has the advantage that there is a buffer stock of turbines available adjacent to the wind farm site, so the site would be unaffected by factors such as extended storm conditions somewhere on the transport voyage route between the manufacturer and site. In general, as a first estimate, it can be assumed that the developer will not want expensive turbine components left partially exposed to the elements for any longer than necessary so approximately 10-20% of the turbines to be installed in any one season can be assumed to be at the marshaling yard at any one time.

The cost of the craneage, SPMT transport units and storage frames associated with a marshaling yard, as well as the port costs (tonnage over the quayside, offloading and loading costs, and quayside leasing, etc.) can be determined and compared with the additional day rate for direct delivery to site using the installation vessel.

It should be remembered that the day rate of transportation vessels is generally significantly lower than that of installation vessels, often less than half and sometimes as much as a fifth or even a tenth of the cost. Under these circumstances, if the turbine manufacturer's premises are far removed from the wind farm site, it is likely that the usage of separate transportation vessels will be inevitable, whereas if the two are very close, the direct transportation and installation using the installation vessel option may be favored.

Direct Delivery of Turbines to the Offshore Wind Farm Sites using an Installation Vessel

In order to gain the maximum utilization of an installation vessel on an offshore site, it is vital that it remains offshore performing installation duties for as great a proportion of its time as possible. This can be achieved by either using feeder vessels to bring turbine components from the marshaling yard (or even directly from the manufacturers) to the offshore vessel – thereby allowing the installation vessel to spend all of its time on site – or by loading multiple foundations or turbines onto the vessel and only returning to the marshaling port after every component onboard has been installed.

If feeder vessels are used, there is a requirement for a vessel-to-vessel transfer of turbine components offshore. The installation vessel to be used on a wind farm will have a crane specified to have adequate capacity to install the various components, but this is when there is a static lifting scenario, and may not be the case if lifting from a floating craft, when dynamic amplification factors must be applied which are in turn dependent on limiting sea states. This is not the case if the feeder vessel is itself a second jack-up barge, as the lifted load is aboard a stable platform, but jack-up vessels are typically slow and expensive and hence often inappropriate for feeder vessel duties.

If a deck barge is used as a feeder vessel, there are metocean wave limits which will impact the amount of waiting-on-weather downtime. Also, the dynamic amplification factors, which have to be applied to the lifted load due to lifting from a floating vessel and which vary with the wave height, mean that there is either a reduced load that can be lifted by the crane or a reduced radius at which lifts can be carried out. This can cause further program delays, if the crane is operating close to its maximum capacity.

As offshore wind project sites move farther offshore, the ever increasing transit time per installation cycle means that, if larger vessels are used, more turbines can be loaded per cycle, and the economies of scale associated with transiting increase. In the past, many offshore turbine installation operations have opted to have the installation vessel collect the turbines directly from the manufacturer's premises (invariably located adjacent to a port, in the case of offshore turbine manufacturers). This arrangement has the obvious and major advantage that it avoids all of the unnecessary double-handling and costs of the marshaling yard, with its attendant cranes, and handling equipment. The cost-benefit analysis is based on whether it is more economical to pay for the additional time taken by the installation vessel to transit between the manufacturer's site and the wind farm, or for the marshaling and delivery costs.

The specifications of the latest offshore wind farm installation vessels position them well as cyclic transport and installation vessels, as the majority of designs are adopting self-propulsion, with transit speeds of 10+ knots.

Offshore Transportation Regulations – Responsible Authorities and Guidelines

Wind turbine and foundation components manufacturers may simply bring their products to the quayside, and allow project cargo forwarding agencies to take responsibility for all other aspects of the delivery, which requires neither specialist skills, nor risk, on behalf of the manufacturer. Sometimes vessels may be simply loaded by manufacturers, with the option of the manufacturer also undertaking responsibility for the sea-lashings. At the other extreme, some manufacturers own and operate a vessel and therefore take responsibility for all aspects of component delivery. Other manufacturers own a vessel but have a third party acting as owner's representative of the vessel who manages all of the day-to-day duties of the vessel owner.

The "hire" contract for a vessel is called a Charter Party, of which there are many standard forms. Chartering vessels to meet transport demands from the spot market, a name given to the fleet of vessels available for charter from their owners, is an option which avoid the capital expenditure of the vessel, but allows manufacturers complete control over the vessel while under their charter. This option is far cheaper than paying freight forwarders for their services, but the charterer takes on the whole responsibility of being equivalent to the vessel owner, and becoming subject to all laws and duties of the sea.

The International Maritime Organization IMO [7] has developed and maintains a comprehensive regulatory framework for shipping and its responsibility today includes safety, environmental concerns, legal matters, technical co-operation, maritime security and shipping efficiency.

The two key sets of rules overseen by the IMO are:

- The International convention for the Safety of Life at Sea, SOLAS [8] regulations; and the
- Convention on the International Regulations for Preventing Collisions at Sea, 1972 [9] There are National bodies responsible for overseeing the 12 nautical mile territorial waters around each country's coast, and many have some level of jurisdiction within their nation's Exclusive Economic Zones. For example, in UK waters this is the Maritime and Coastguard Agency, MCA [10]. The MCA issues numerous Marine Guidance Notes, the most significant of which is:
    - MGN 371, "Offshore Renewable Energy Installations (OREI) – Guidance on UK Navigational Practice, Safety and Emergency Response Issues" [11].

When transporting turbines directly to sites, the delivery voyage becomes part of the Construction, and will come under various regulations relating to that role, including the Health and Safety regulations governing that function. Furthermore, for all shipping, there are marine transportation regulations relating to factors such as the stability calculations, deck strength calculations, and the provision of regular weather forecasts.

3.2.5 Foundation Installation

Monopile Foundations

A monopile foundation consists of a single, steel pile, which is embedded into the sea bed. The depth of pile penetration into the sea bed, the pile diameter and wall thickness are all determined principally by the maximum water depth, the rated capacity of the wind turbine and the local seabed soil conditions. The majority of foundations installed to date at offshore wind farms are steel monopiles.

The advantages of this foundation type from an installation perspective are that it is relatively cheap to manufacture; requires little or no seabed preparation, and, in a wide-range of soil conditions, can be installed with one simple piling operation. Figure 3-9 shows a typical monopile foundation design.

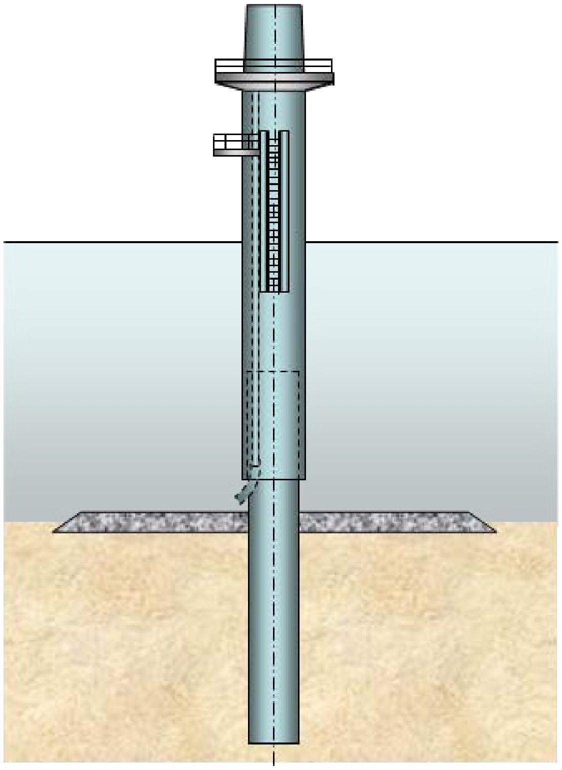


Figure 3-9: Example of a Typical Monopile Foundation Design with Grouted Transition Piece

Typically, the turbine tower is mounted onto the foundation via a transition piece which itself is fixed onto the pile using a grouted joint. The hard, cement-like grout is pumped into the annulus between the monopile and the transition piece and allowed to cure prior to installation of the turbine. A grout seal around the base of the annulus, typically fabricated from a rubberized polymer, should prevent the grout from flowing out into the sea. The purpose of the grouted joint is to take up any misalignment tolerances that inevitably occur during installation of the monopile, and provide continuity of structural load transfer between the monopile and the turbine tower. The transition piece will also typically include all the secondary steelwork such as boat landing (see Section 4.2.1), ladder, walkways, and cable routing (such as J-tubes), all of which would be unlikely to withstand the loading exerted on the structure during piling.

Transportation to Site

The method employed for transporting the monopiles from the manufacturer's facilities to the offshore wind farm site greatly affects the offshore installation operations. Monopiles can be transported in a number of ways including:

- Plugging the pile and floating it to site with tug vessels using its own buoyancy;
- Loading one or more piles onto the deck of the installation vessel;
- Using a feeder vessel to transport the piles out to site. Suitable feeder vessels include:
    - Towed deck barges, with or without spud-legs (requires dynamic offshore lifts);
    - Jack-up barges to enable static offshore lifts (more expensive than deck barges);
    - Floating crane vessels, with or without heave-compensated craneage (costly);
    - Cargo vessels with or without cranes fitted (fast, but dynamic lifts).

Source: GL GH

Figure 3-10: Monopiles Being Loaded onto a Deck Barge by Sheerleg Crane

Installation

Installation of monopiles is dependent on soil and seabed conditions. The main installation methodologies currently used are:

- Driven;
- Drive-Drill-Drive; and
- Drilled (rock-socketed).

These approaches are described in more detail in the following sub-sections.

Pile Driving

When soil conditions allow, it is usual to install monopoles by simply driving them into the seabed using a large piling hammer. The most common installation methodology is to use a jack-up vessel as a piling guide, and to use the onboard crane to both lift the pile into a guide-frame (also called the piling gate), and place a hammer on top for pile-driving, as shown in Figure 3-11.

Source: Dong Energy, Burbo Bank Offshore Wind Farm

Figure 3-11: Steel Monopile being Driven by a Menck Hydrohammer – Jack-up *Excalibur*

Lifting the pile vertical usually requires cranage with a lift capacity in excess of the weight of the pile due to the dynamic element induced by rotating the pile and lowering it into the water. However, two exceptions to this vessel crane lift-capacity limitation exist:

- A technique called semi-buoyant lifting, in which the pile is plugged and the lift-weight seen by the installation crane is reduced. This technique potentially allows installation vessels with relatively small lift capacities to install heavy foundations. It does, however, require complicated marine operations planning and supervision, and is not a preferred technique for most installation sites.
- A specialist piling frame, for example as fitted to the Excalibur Jack-up, which has a jack-up pile-guide which lifts and rotates the pile into the vertical, independently of the crane, as shown in Figure 3-12.

Source: GL GH, Gunfleet Sands Wind Farm

Figure 3-12: Piling Frame on Excalibur Awaiting a Floating Monopile

Monopile diameters installed to date have varied from 4 m upwards and diameters of 6.5 m or larger are being discussed for installation in wind farms in the future, with forged piling hammer anvil diameters being the limiting factor. At present there is an effective limit of approximately 7 m diameter. There are plans to synchronize multiple hammers on one pile, which could potentially remove this upper limit. This would result in the potential to utilize monopiles with larger turbines and in deeper waters, before recourse to jackets or other designs would prove necessary; however, this approach has yet to be successfully developed and demonstrated.

Monopile weights vary with water depth and turbine size, as well as wave climate severity and soil strengths, and have typically ranged between 250 and 500 metric tons to date. Heavier monopiles are likely in the future, potentially as heavy as 800t or more if the design limits are pushed to allow monopile foundation designs for wind turbine sizes of 5 and 6 MW and their use in water depths of over 30 m.

A key design factor is usually fatigue life. Great care must be taken regarding the planned driving sequence during monopile design, as driving the pile too hard could reduce the fatigue life of the monopile below that needed for the 20-year wind turbine design life operation.

Drive-Drill-Drive Technique

The ground conditions at some sites (or specific areas of some sites) include layers of harder material which cannot be driven through without damaging the pile. The monopile installation technique in these circumstances is typically to “drive-drill-drive”. This consists of driving the pile down to the harder layer, before using a large-diameter reverse circulation drill, passed down the inside of the monopile, to remove the upper layer, and then drill through the hard layer. The drill is generally at a slightly smaller diameter than the monopile to ensure subsequent good contact between the pile and the soil. Subsequently the drill is removed and the pile is driven down to its target depth.

Clearly, the drilling produces material which must be disposed of. The type of disposal of these up-risings is highly dependent upon local environmental conditions and sensitivities. The following approaches are therefore chosen depending on site-specific consenting:

- **Disposal on site:** If it is acceptable, under the environmental consent, to simply deposit the waste materials on site, they can be potentially valuable in adding to any scour protection required to ensure that the pile is not undercut.
- **Process and disposal on site:** If environmental consents require that no turbidity is imparted to the water column, methodologies to remove, and safely dispose of substantial amounts of material are needed. Large quantities of water are required, as this water must travel at considerable speed to maintain the cuttings in suspension. Processing can be achieved by a number of methods. The water can be passed over a flow-path incorporating several weirs, laid out on a dedicated barge, possibly with added flocculants such that material falls from suspension in the slow flowing waters. Another alternative is the usage of a system of fabric or sand filtration. The solids may then be flocculated such that they may be returned to the seabed without dispersal back into the water.
- **Disposal onshore:** A similar approach to the above, except that the filtered solids are transported for safe disposal onshore using a barge or equivalent.

The drive-drill-drive technique is clearly more time-consuming than simply driving the pile, and given that jacket-leg piles can be driven through harder sub-strata, it would appear logical to revert to jacket foundations if monopiles cannot be driven. However, given the large price differential between the monopile and steel tubular jacket-structures, and the seabed preparation which they sometimes require, it is often economical to carry out these additional drilling operations rather than reverting to the installation of jackets.

This same reverse circulation drilling equipment is often required as a contingency, if site investigation shows great local variations in ground conditions, or in areas where there are known to be glacial till deposits, as glacial scouring often entrains large boulders, which may require drilling, to allow the pile to achieve target depth.

Rock-Socketing

Clearly, where the monopile is to be installed in rock or very hard soils, piling is inapplicable. However, monopiles have been installed in rock using “rock-socketing techniques”, which utilize large diameter pile top reverse circulation drill-rigs to drill a hole slightly larger in diameter than the monopile. The monopile is then lowered into the socket, and is grouted in place. Two early offshore wind farms have installed monopiles in this way to date – Blythe in the UK, and Yttre Stengrund in Sweden. Generally, these techniques are limited to approximately 5 or 6 m diameter monopiles. Increases in diameter imply increases in up-risings (material removed by the drill) in proportion to the diameter squared. This leads to increases in machinery size, power requirements, and greatly reduces drilling rates in equivalent ground conditions.

Disposal of the large quantity of up-risings will need to be performed using one of the methodologies discussed above for the sub-section on drive-drill-drive piling, depending upon local environmental constraints.

Currently, one of the largest drills is the Fugro Seacore Toredo 90, shown in Figure 3-13. It can drill 6 m diameter holes in hard rock, and can drill larger holes in softer materials, often using smaller pilot holes and under-reaming techniques. It is shown here fitted to the piling rig on the aft-end of the jack-up Excalibur.

Source: Fugro Seacore Toredo 90 specification sheet

Figure 3-13: Fugro Seacore Toredo 90, Mounted on Jack-Up Vessel *Excalibur*

This technique is considerably slower than impact piling. However, the very nature of seabed conditions which might require a rock-socketing approach also implies that there is unlikely to be a requirement for seabed preparation or scour protection. It has a further advantage that no piling noise is generated, so there are some sites where this technique may afford the opportunity to install foundations during periods where environmental assessments have concluded that piling noise would be unacceptable.

Transition Piece Installation

The methodology adopted for the installation of transition pieces is generally much more flexible than for the heavier monopiles. Typical transition pieces weigh between approximately 200 and 300 metric tons and hence are well within the capabilities of the vessel and crane used for the installation of the monopile. Similarly, if a floating vessel is used, sea-state conditions in which transition piece installation may be conducted are likely to be somewhat less stringent than those required for the monopile installation works. However, to free up the monopile installation vessel earlier, the transition pieces may be installed and grouted independently using a floating or jack-up vessel with adequate cranage.

The grouting between the monopile and transition piece may be carried out by utilizing a grout spread on the installation crane vessel, but there is a strong case for employing a separate vessel to carry out this function. After the placement of the transition piece, final verticality and height adjustments using hydraulic jacks do not require attendance of an expensive installation vessel, which can instead continue to the next foundation location and begin upending and placement of the next monopile. The grouting vessel can then monitor the leveling of the transition piece, prepare and pump grout into place and, after the grout has cured sufficiently, remove the hydraulic jacking mechanisms.

Source: Offshorewind.biz

Figure 3-14: Jumbo Shipping *Jumbo Javelin* Heavy-lift Cargo Vessel Installing Transition Pieces and Grouting at the Anholt Offshore Project

It should be recalled that a full curing time is also necessary before the turbine can be fitted atop the newly grouted transition piece. Often, since different vessels are involved, there is a delay of several weeks before the turbine is fitted. It is typically required that foundations, especially those on the wind farm’s extremities, be fitted with temporary navigation lights, radar reflectors, and other aids to navigation such as AIS transponders, until aids to navigation on the wind turbines are fully commissioned.

It is noted that grout failures between monopiles and transition pieces have been prevalent across many European offshore wind projects. Newer projects are therefore considering modifications to this critical joint such as the inclusion of sheer keys (typically beads of weld) on both transition piece and monopile bonded surfaces.

Scour Protection

Monopiles present a large obstruction to flow and, if deployed in areas where currents, tidal flows, or wave-induced erosion are commonplace as well as areas featuring fine or mobile seabed sediment, scour protection will typically be required to maintain sufficient burial.

The methodology generally employed is to lay a filter layer of small material, normally around 100 mm diameter, before piling to act as temporary scour protection immediately after the pile is driven. Subsequently, heavier material is deposited over the filter layer, to permanently protect the seabed from erosion by wave, tide, or current action. In areas where there is severe wave action, and relatively shallow waters, rock armor with individual component weights in excess of a half-ton is not uncommon. Clearly, care needs to be taken to ensure an appropriate cable route through or underneath the scour protection without exceeding cable bending radius limitations or damaging the cable.

In shallow sites, when large waves churn the seabed during heavy sea conditions, this can lead to seabed migration, and erosion due to horseshoe vortices around the pile may require that scour protection be deposited. Careful analysis of the particle sizes in seabed material is required during site surveys to allow scour protection calculations to be carried out with accurate data.

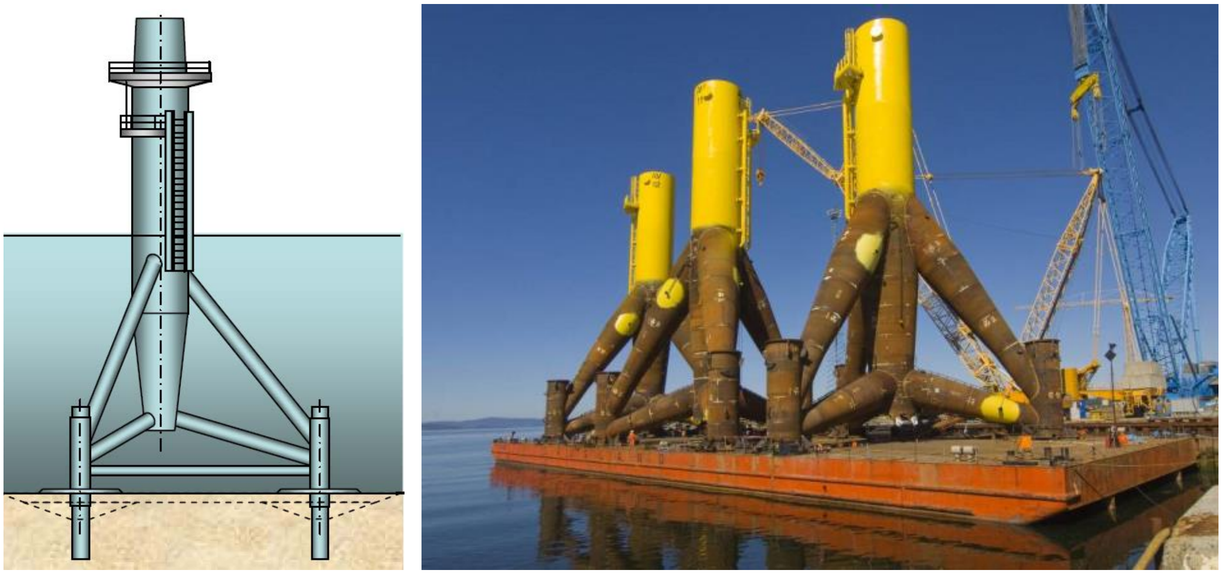
Space Frame Structure Foundations (Jackets and Multi-pods)

For locations with greater water depths or large turbines, space frame structures are likely to be considered. Broadly speaking these concepts fall into two categories: (i) multipods, including tripods, and (ii) jackets. These designs transmit forces to the foundations in the sea-bed via a multi-member structure, with the aim of minimizing the ratio of mass to stiffness. Typically long, small diameter pin-piles are used to fix space frame structures to the seabed, although suction caissons have also been suggested. Since jackets are very large and unwieldy, it is un-economic to transport the finished structures over large distances, though there are final assembly options which allow for substantial proportions of the fabrication work to be sub-contracted, resulting in more economically transportable sub-assemblies.

Tripods

The tripod is a standard three-legged structure made of cylindrical steel tubes. The central steel shaft of the tripod acts as the transition to the turbine tower. The tripod can have either vertical or inclined pile sleeves onto or into which corresponding pin-piles are grouted. The base width and the pile penetration depth can be adjusted to suit the actual environmental and ground conditions. The piles in this case would be relatively thin with respect to monopiles at nominally 1.5 to 3 m in diameter.

As with monopile designs, the dimensions of multi-pod foundations will increase with turbine capacity and water depth and will also be linked to the site-specific metocean conditions. However, indicatively, pin-pile separation is likely to be in the range 20 to 40 m, therefore requiring considerable deck space during transportation to site.



Source: GL GH

Source: Alpha Ventus

Figure 3-15: Indicative Tripod Design (left), Tripod Foundations for Alpha Ventus (right)

Tripods are heavy structures and typically beyond the capability of all but the heaviest-lift jack-up vessels. For this reason, early installation methodologies involved sheer-leg cranes, such as the *Taklift 4*, shown in Figure 3-16. The metocean limits imposed by Marine Warranty Surveyors for placement of such heavy objects on the seabed in dynamic conditions can lead to extended "waiting-on-weather" periods. However, some vessel providers are considering the development of very heavy lift jack-up vessels which have the potential to greatly improve the metocean limits for this key marine operation.

Source: Alpha Ventus website

Figure 3-16: *Taklift 4* at Alpha Ventus

Jackets

Jackets differ from tripod-type structures in that the design has:

- A large plan area for the majority of the structure with the positioning of steel farther from the center of axis, resulting in significant material savings;
- Generally four-leg designs deployed to date, although 3-leg designs are also feasible;
- A more complex structure and hence greater welding and fabrication effort;
- A more consistent cross-section for the tubular elements, with potential to avoid conical elements; and
- Potential for marginally lower crane vessel hire costs due to the lower lift weights.

It should be noted that, as with tripod foundations, there is a shortage of suitable installation vessels for jackets, which has led to the use of over-specified and expensive floating cranes with low sea-state operating envelopes (~0.75 m Hs).

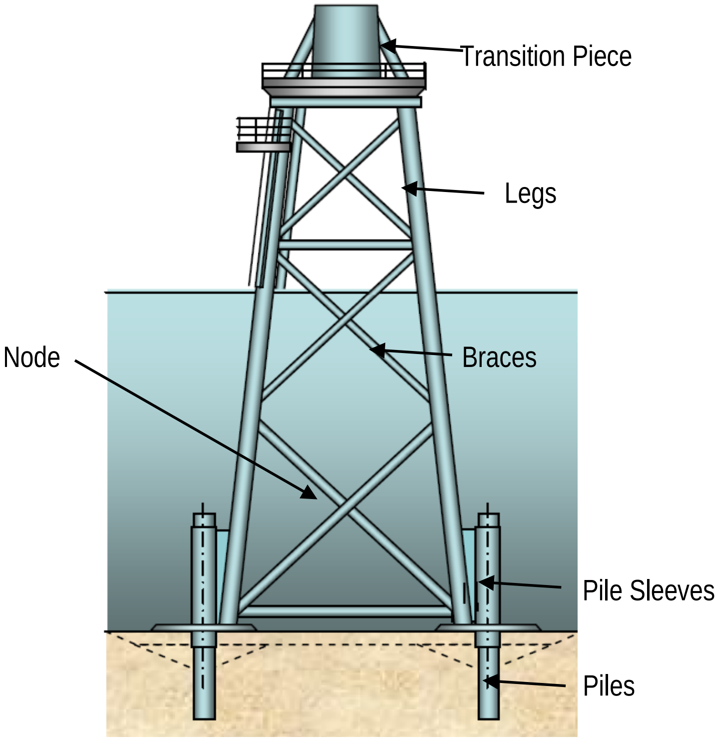


Figure 3-17: Example of a Typical Jacket Design with Nomenclature

Jacket sizes tend to be approximately 15 m^2 plan area in shallower sites, and up to 25 m^2 for deep sites, with the tower flange being located in the order of 20-30 m above sea level. Weights typically range from 350 up to 800 metric tons, but the jacket weight for any particular water depth is usually significantly lower than that of an equivalent monopile design.

Transportation to Site

Depending on whether post- or pre-piling is chosen (see Installation sub-section below), the pin-piles and space-frame foundations may be transported to site together or as entirely separate installation activities. Pin-piles and space-frame foundations may be transported to site in a variety of ways.

Transportation of Pin-piles

Pin-piles are usually transported in sets of three or four, corresponding to a whole number of complete foundations. Floating feeder vessels are a relatively attractive option for the transportation of pin-piles since the reduced lift weights involved require less stringent sea-state restrictions on dynamic lifting. If post-piling is adopted as the installation strategy (see next section) and the installation vessel is used to collect the space-frame foundations from the quayside, then the pin-piles will typically be transported on the same vessel. However, if pre-piling is to be adopted or the space-frame foundations are to be transported to site by a feeder vessel, then there are multiple transportation options available for pin-piles including:

- Loading directly onto the deck of the pin-pile installation vessel;
- Using a feeder vessel to transport the piles out to site. Suitable feeder vessels include:
    - Towed deck barges, with or without spud-legs (requires dynamic offshore lifts);
    - Cargo vessels with or without cranes fitted (fast, but dynamic lifts);
    - Jack-up vessels (only an obvious choice if the installation vessel is also a jack-up vessel, thus avoiding dynamic lifts).

Transportation of Space-frame Foundations

Due to the large plan dimensions of jacket or tripod foundations, deck space is a key consideration for their transportation and hence jack-up vessels are seldom used, as deck space is often limited. Normally considered options include:

- Loading directly onto the deck or slung from the crane of the installation vessel;
- Using a feeder vessel to transport the structures out to site. Suitable feeder vessels include:
    - Towed deck barges, with or without spud-legs (requires dynamic offshore lifts);
    - Cargo vessels with or without cranes fitted (fast, but dynamic lifts);

Source: Scaldis Salvage and Marine Contractors website

Figure 3-18: Scaldis *Rambiz* Offloading Jackets from a Deck Barge at Ormonde, UK

Installation

As with monopile installation, pin-piles for space-frame foundations can be installed using pile driving, drive-drill-drive techniques or rock-socketing. For more details on these approaches, see the relevant sub-sections under monopile installation above.

In monopile driving, the requirement for verticality has tended to favor the use of jack-up vessels. Pin-piles can also be installed using jack-up vessels, but since these are comparatively lightweight and are driven with pile-guides located on the seabed, there is a reduced vessel capacity requirement for piling operations and greater flexibility with regard to the use of floating vessels. The piles are generally 1.8 m to 2.5 m in diameter, have target penetrations below seabed of around 50 m and weights of the order of 100 to 200 metric tons each.

For the installation of tripod or jacket foundations, two alternative installation approaches are used:

- **Post-piling:** Placing the space frame structure on the seabed and driving the piles through permanent pile-guide sleeves (or skirts) fitted to the legs of the structure and grouting in place;
- **Pre-piling:** Pre-driving the piles using a template and then lowering and grouting the space frame structure onto the piles.

Post-piling

Assuming that the seabed is level (or has been leveled for the turbine micro-siting to a level area within the vicinity of its proposed location), the sequence of offshore operations for post-piling is as follows:

- Lowering the space frame structure to the seabed;

- Locating a pile into the sleeve on each leg of the structure;
- Driving/drilling the piles and grouting.

The primary advantage of this approach versus pre-piling is that it does not require a separate piling template to be fabricated, placed on the seabed prior to pilling and removed afterwards. The main disadvantage is that the pile-guides need to be substantial structures to survive the piling operations, and this adds approximately 10% to the overall weight of each structure. Not only does this increase material and fabrication costs, but also requires a larger installation vessel, as the space frame structure lift is the largest lift and hence is the primary driver for vessel selection.

Furthermore, this approach only allows for space-frame designs wherein the pin-pile passes through the pile sleeve. The methodology does not allow for space-frame feet which locate into the insides of the pin-piles.

Pre-piling

For this installation approach, a complete or modular template is first located on the seabed. In the case of modular templates, the piling frame is moved to each of the 3 or 4 location points and fitted into position using guide-pins. If piling from a jack-up vessel (normal practice to date) the template may be slung underneath the jack-up when not on the sea bed, as in Figure 3-19. The use of moon-pools through the installation vessel deck may allow all pin-piles to be installed without moving the vessel, particularly relevant to jack-up vessels.

Source: Temporary Works Design BV website and GeoSea

Figure 3-19: Piling Frame Used at Ormonde Slung Underneath GeoSea's *Buzzard* Jack-up Vessel

After the piling is completed at the current turbine location, the piling frame is removed, leaving the four piles positioned on the seabed ready for the space-frame structure to be lowered and leg-extensions located over or into the tops of the pin piles. This is a comparatively quick operation, and can be carried out equally from either a jack-up or a floating craft.

Jackets or multipods can be installed in rapid succession once the pre-piled foundations are in place. Figure 3-20 below shows batch delivery of jackets on sea-going transport barges, from which they can be simply lowered into place. Grouting can be carried out by the same vessel, but is often done by a separate dedicated floating craft.

Source: Alpha Ventus website

Figure 3-20: Jacket Structures on Barges Awaiting Installation in Pre-Piled Foundations

Source: Talisman/Beatrice website

Figure 3-21: *Rambiz* Up-ending a Leg-Sleeved Jacket at Beatrice

Grouting or Swaging

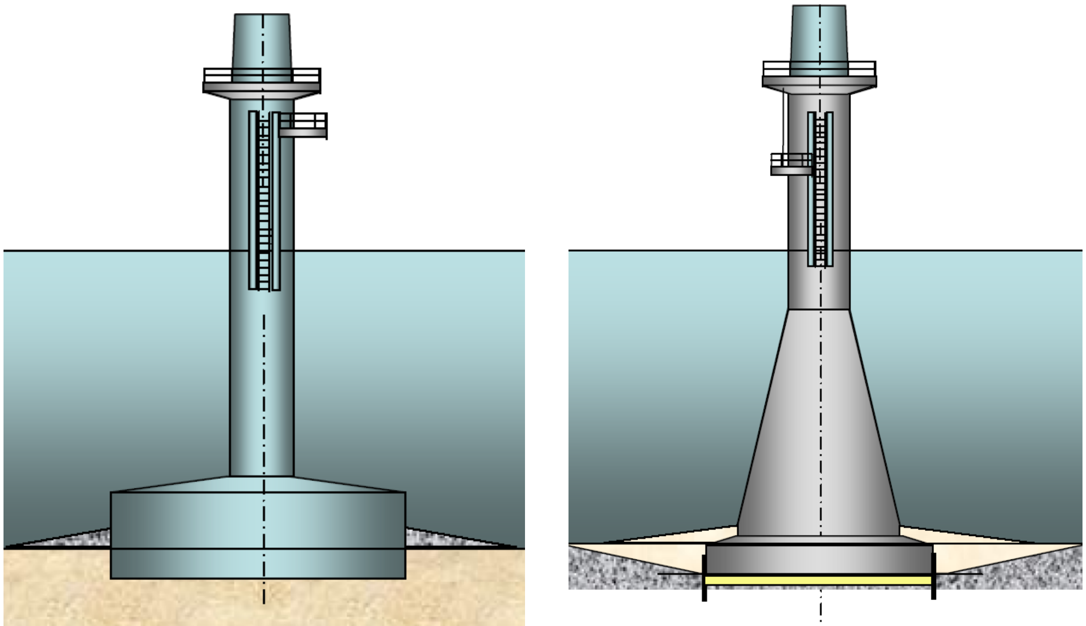
Connection of pin-piles and space frame structures can be achieved by either grouting (industry norm) or swaging:

- **Grouting:** The primary approach to date involves pumping the structural, high-strength grout into the annulus between the pin-pile and the piling sleeve or spigot. Much like the connection between monopiles and transition pieces, a rubberized grout seal at the base of the annulus should prevent the grout from flowing out prior to curing.
- **Swaging:** This process involves deploying a specialized tool inside the pin-pile. Water is pumped through this tool at very high pressure, which forces the pile to expand and deform outwards into a specially cut groove on the inside wall of the pile sleeve. This process usually takes about 2 hours per pile and has the benefit of avoiding the use of cement grout, while avoiding the generation of any significant noise. However, there remain questions about the effectiveness of this process for structures subject to high levels of fatigue.

Gravity Base Structures

Gravity Base Structures (GBS) typically take one of two basic forms; narrow shaft or conical, as illustrated in Figure 3-22. Although steel GBS foundations have been proposed, those that have been deployed to date have been fabricated in concrete for cost-related reasons. Hence, this type of structure is sometimes termed a Concrete Gravity Structure (CGS).

To date all GBS foundations for wind turbines, except those at Thornton Bank (consisting of 6 turbines in about 25 m of water), have been installed at rather shallow water sites. Thus the required lifting capacity has been well below 2,000 metric tons, ensuring that the transport and installation of the foundations could be executed using inexpensive barges customized for the installation process. For some projects such as Middelgrunden just outside Copenhagen, Denmark, the foundations were manufactured in a dry dock and transported to site partly submerged, thereby reducing the lifting capacity required.



Narrow shaft GBS

Conical GBS

Figure 3-22: Gravity Base Structures (GBS)

Transportation to Site

Due to the considerable weights involved, the transportation of GBS foundations to site is intrinsically linked to the installation methodology. The following approaches are applicable under corresponding installation strategies:

- Slung from the crane of the installation vessel either above the water or partially submerged (e.g. sheerleg) (see Figure 3-23);
- Using a deck barge as a feeder vessel (adds the further option for fabrication of GBSs on the deck barge(s), thus avoiding very heavy lifts at port);
- Floated out (un-ballasted or partially ballasted GBSs may be designed to float, which could add the additional benefit of fabrication within a dry dock to avoid very heavy lifts at port).

Source: International Marine Consultancy website

Figure 3-23: Scaldis *Rambiz* Sheerleg Vessel Transporting a Partially Submerged GBS to Thornton Bank Offshore Project in Belgium

Seabed Preparation

GBS structures require large surface areas to be in contact with a firm, level seabed to develop the extremely large overturning moments required to react the turbine loadings. To achieve this seabed, preparation is often necessary.

If the local seabed comprises soft material, such as silt, soft clay, or other fine deposits, then it will be necessary to excavate this overburden down to a more solid layer. Furthermore, if tidal or wave-induced currents are commonplace at the site, then scour is also likely to be prevalent around the foundations, which should be prevented ideally as part of the seabed preparation works or with additional scour prevention material after the GBS is installed.

If significant deposits of overburden material are present at particular points in the site, it may be necessary to restrain the surrounding material to ensure that it does not flow into the area which has been excavated. Various methodologies exist for carrying out such an operation. It is possible to have a dredger and fall-pipe vessel (see Section 3.4.8) working in close cooperation. This affords the opportunity of removing softer overburden material, and immediately backfilling with stronger, probably granular, fills. Alternatives include a variety of methodologies for forming a temporary cofferdam around the excavated area to retain the surrounding materials. While sheet piling around the area would also be technically feasible, the expense would probably be prohibitive. Alternatively, it is worth considering placement of sandbags or rock armor on the surface of the seabed, excavating the area within these sandbags or armor and allowing them to fall to the seabed under their own weight, thereby acting as a retaining wall. This approach lends itself to acting as a form of both seabed preparation and scour protection at the same time, which is generally required by GBS structures.

Installation

The way GBS foundations are installed depends to a large extent on the method in which they are fabricated. The difficulty with offshore GBS installation lies in the weight of the structure. To handle this weight, there are several different methodologies:

- Assuming the GBS is fabricated on the quayside (or transported to the quayside once constructed), a sufficiently powerful heavy lift crane vessel, such as a sheerleg, is required to lift the GBS directly from the port and transport it to site for installation. Alternatively, multiple GBSs can be loaded onto a barge using the heavy lift vessel, then transported to the site, where the heavy lift vessel is used again to lower them onto the seabed.
- Assuming the GBS is fabricated on a barge, the barge needs to be taken to the site, where a sufficiently powerful heavy lift crane vessel is required to lift it from the barge and onto the seabed.
- Assuming the GBS is constructed in a dry dock, there are two options for transportation to the site and installation. The GBS can be made semi-buoyant and towed to site, using a barge with a frame/support structure, or a crane vessel supporting the weight of the GBS. Alternatively, the GBS can be made fully buoyant and towed to site using an appropriate barge or vessel. Once on site, the GBS can then be ballasted and lowered. There are a number of ways the ballasting and lowering could be performed, but it is envisaged that initially water would be used as ballast and then later replaced with a heavy aggregate once on the seabed. Lowering would need to be controlled either by one or more crane vessels (albeit with much less lift capacity than the dry lift weight of the GBS would require) or potentially using two or more vessels with moon pools and appropriate lowering tackle.

Ice Cones

In waters where sea ice does not form, the tower of the GBS generally tapers down to a close approximation of the diameter of the base flange diameter of the turbine tower. However, when considering areas which are subject to ice coverage such as the Great Lakes, single-sided or double-sided conical structures must be fitted to the tower to break up the ice and hence limit the lateral loadings on the structure from the moving ice. GBS foundations lend themselves to this modification due to their cast concrete fabrication, although monopiles or associated transition pieces could theoretically be modified in a similar fashion. Similar structures have proven effective in the past and recently guidance has been issued in the form of "ISO 19906:2010 Petroleum and Natural Gas Industries - Arctic Offshore Structures - 1st Edition" [12].

3.2.6 Wind Turbine Installation

The assembly of the turbine onto the selected foundation type involves a number of operations, some of which require considerable precision and stability. For this reason the majority of offshore turbine installation to date has been conducted using jack-up vessels to provide the necessary stability at the significant lifting heights required. Furthermore, many turbine components have maximum acceleration limits set by the manufacturer for load-out, transportation, and installation and hence offshore handling operations, such as dynamic lifts from feeder vessels, must be carefully considered when selecting an approach to turbine transportation and installation.

Transportation to Site

The manner in which turbines are transported to site will depend upon multiple factors, not least:

- Distance of the site from the marshaling port;
- Installation methodology (chiefly the number of separate components);
- Turbine size; and
- Manufacturer warranties (regarding maximum allowable accelerations on components).

Principally two options are available to installers for the transportation of turbines, namely on the installation vessel (most common to date) or on a feeder vessel; these can be broken down as follows:

- Transportation by the installation vessel (majority of projects to date):
    - Load-out of individual components on the deck of the installation jack-up (typically 2 to 10 turbines per journey);
    - Load-out of turbine sub-assemblies on the deck of the installation jack-up, e.g. whole rotors or bunny ear configurations (typically 1 to 3 turbines per journey);
    - Pre-assembled turbine slung from the crane of the installation vessel (1 turbine per journey).
- Transportation of turbines by feeder vessel(s) such as:
    - Deck barge with tugs (requires dynamic lifting of delicate turbine components);
    - Heavy cargo vessel with or without onboard cranes (requires dynamic lifting of delicate turbine components);
    - Second jack-up vessel (avoids dynamic lifts, but more cluttered deck).

Installation

It is always desirable to keep the number of offshore operations to a minimum. However, a number of compromises are forced upon the assembly sequence, resulting in an optimum solution lying anywhere from installation of a largely pre-assembled turbine to offshore assembly of a large number of smaller components. The full range of installation options for turbines is summarized in Table 3-4.

Table 3-4: Wind Turbine Installation Options

	Total Number of Lifts	Lift Number						
		Lower Tower	Upper Tower	Nacelle	Hub	Blade 1	Blade 2	Blade 3
Individual blades with 2-part tower.	7	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Individual blades with 1-part tower	6	*1*		*2*	*3*	*4*	*5*	*6*
Bunny ears with 2-part tower	4	*1*	*2*	*3*				*4*
Bunny ears with 1-part tower	3	*1*		*2*				*3*
Pre-assembled rotor with 2-part tower	4	*1*	*2*	*3*	*4*			
Pre-assembled rotor with 1-part tower	3	*1*		*2*	*3*			
Fully pre-assembled tower-top assembly, on upper half of the tower	2	*1*	*2*					
Fully pre-assembled	1	*1*						

Clearly, installing all components offshore requires a greater number of weather-restricted offshore activities; however, it also typically allows for many more turbines to be transported to site with each journey due to the efficient racking of blades (see Section 3.2.3), so can be advantageous overall, especially if the installation vessel is to be used for the transportation of components to site, as is typically the case.

The key lift is usually the placement of the nacelle on top of the tower. This is normally the heaviest lift and it is also extremely high (in some of the lift sequences the fully assembled tower may be heavier). It is usual to have approximately 20-25 m between the lowest point of the blade-path, and sea level at highest astronomical tide (HAT), which then determines the hub height of the turbine. For example, in the UK this minimum clearance is dictated by the Maritime and Coastguard Agency's Marine Guidance Note 371 – *"Offshore Renewable Energy Installations"* [13]. Hence with a 125 m diameter turbine, the hub height will be typically around 85 m above HAT.

Assembly of the nacelle, with the hub and two blades in the "bunny ears" configuration (so-called as the blades resemble a rabbit's ears) means that four of the seven turbine components can be assembled in a single lift, and the offshore assembly time is somewhat reduced. However, this requires significant deck space if it is pre-assembled onshore. It also requires that the crane have the capacity to lift the weight of all four components simultaneously to the top of the tower and requires additional time to exchange the lifting tackle to lift and rotate the final blade into place.

Turbine manufacturers do not usually publicly specify which configurations they will permit during installation; however, as an example, Vestas has historically allowed its turbines to be installed in the bunny ears manner. Vestas has generally designed lightweight turbines, which increases the range of installation cranes able to undertake this lift together with the associated lifting gear arrangement (which must be included in the lifted load calculation).

As turbines have increased in size, so has the moment exerted on the rotor when an incomplete number of blades (1 or 2) are installed midway through offshore assembly. Furthermore, if the blade lifting tackle and methodology are restricted to one blade orientation, as is often the case, the rotor must be turned between each blade installation. Therefore single-blade assembly techniques require that the turbine gearbox design is driven by the maximum torque during installation rather than the maximum torque during power generation. To avoid this, larger turbines installed to date have mostly relied upon an installation sequence which involves the complete rotor (hub together with three blades) being installed in one lift, which imparts no out-of balance torque on the main shaft, as shown in Figure 3-24.

Source: Alpha Ventus website

Figure 3-24: Full Rotor Assembly being Fitted to Areva Multibrid M5000 Nacelle

It is possible to install a turbine in a single lift and this has been done on two wind farms to date – Beatrice in the UK, Figure 3-25, and Donghai in China. This requires very heavy crane capacity, and calm sea conditions.

Source: Scaldis website

Figure 3-25: Installation of Fully Assembled REpower 5M Turbine at Beatrice

Advantages of single-lift turbine installation include a shortened offshore commissioning time, as much of the commissioning can already have been performed onshore and the ability to install turbines in very deep water where the choice of installation jack-up may otherwise be limited by leg lengths.

Limiting Operational Conditions for Turbine Lifts

Each turbine manufacturer will specify limits within which each particular operation during the assembly of its turbine can be carried out safely:

- The tower sections are large and present a large surface area to the wind, but are aerodynamically symmetrical, and can be safely lifted in wind-speeds of the order of 12 m/s.
- The nacelle presents a relatively small profile, and is heavy, so is relatively unaffected by winds.
- It is the blade lifts that present the greatest problem. Whether pre-assembled into a bunny ears configuration, lifted as single blades, or lifted as a complete rotor, the very large lift-surfaces can generate lift-forces which can cause the load to move if not adequately constrained, in even light winds. Current systems involve holding blades with ropes, and frames, which restrict movement, but at best, lifting blades is limited to wind speed conditions around 8m/s, which is below the average wind speed for many sites. While work is being performed to develop frames to assist in restraining blades during assembly, the high winter wind speeds will generally reduce opportunities for turbine installation until the summer months.
- Any dynamic offshore lifts, such lifting off a feeder vessel, will be very limited by sea-state conditions and crane lift capacity/speed. Values as low as 0.5 m Hs are not unheard of.

Commissioning

Once installation of the turbine is complete, considerable commissioning effort (often several days) is usually required before the turbine can commence exporting power. Commissioning generally includes electrical connections between all the various components, final bolting and torque checks, electrical and functionality checks and an initial running period (often at reduced output).

This work can normally be carried out by a team of technicians (often future O&M maintenance crews) accessing the turbine with a work boat (and hence usually limited to working up to a significant wave height of around 1.0 to 1.5 m).

3.2.7 Cables and Electrical Installations

The majority of insurance claims and post-installation remedial works to date on offshore wind farm sites have related to cables. This apparently simple operation has proven extremely difficult and both developers and insurers have grown increasingly wary of appointing contractors without a long proven track record in the field. Unlike wind turbines, some aspects of balance of plant items such as substations and export cables can prevent the export of power from a large proportion of the project. It is therefore of critical importance to ensure that these key items are properly installed and do not lead to undue failures or remedial works once the project is operational.

The majority of cable and electrical infrastructure installation works can be undertaken in parallel with the foundation and wind turbine installation works. The primary exceptions to this are:

- It is normal, though not necessarily essential, to install the foundations at either end of an array cable prior to laying that array cable;
- Wind turbines often require a power supply to maintain auxiliary systems and lubrication pumps etc. Therefore it is common practice to install the export cables, offshore substation (if applicable) and the relevant array cables prior to installing each turbine. This approach also allows assets to start generating revenue as soon as possible after installation. However, diesel generator units have been used in the past to circumvent this requirement.

Subsea Array Cables

The inter-array cables on a wind farm are generally 33 kV-36 kV 3-phase cables, and normally require some degree of seabed embedment, or, on harder seabed or rock, some other system of protection. At each wind turbine or substation structure, the cable passes up either an “I”- or “J”-tube, depending upon the foundation design, with J-tubes being the most common to date. The purpose of this tube is to support the cable as it passes up the foundation and, in the case of J-tubes, to support the transition from the horizontal to vertical and maintain a constant radius. I or J-tubes are typically installed as part of the secondary steelwork connected to the foundation or transition piece and hence the cable must be pulled up through these tubes as part of the installation process.

The distances between turbines perpendicular to the prevailing wind direction are usually around five turbine diameters, while distances between rows are typically in the range of around seven and a half rotor diameters in order to reduce wake losses. For 5 MW machines with approximately 125 m rotors, this leads to indicative turbine separations of ~625 m and row separations of ~875 m. Therefore, depending on which array cable layout is adopted, each span in the array cable will have a length in this range, at least in areas of the wind farm where there is a regular grid pattern.

Cable Routing

Cable jointing is carried out within the base of the turbine tower or the transition piece. Turbine arrays are laid as a number of radial strings rather than as “ring circuits”, although some wind farms do have the ability to export a limited amount of power through inter-string connections if a main array string cable failure occurs for some reason. Normally the last turbine on an array cable string has one cable entering the foundation, while other turbines have two, unless located at a branch, in which case three cables all enter the foundation. In such instances there are three cables in relatively close proximity on the seabed and the complexity of this should not be underestimated from the point of view of cable protection and identification of safe areas for jack-up footprints.

On most offshore wind projects the array strings terminate in one or more offshore substations. Close to the substation, a large number of cables all converge, adding greatly to the complexity of the local seabed. It is therefore advantageous to ensure that no cables arrive at the substation on at least one side to allow jack-ups or anchored heavy lift vessels to operate safely from at least one direction.

Load-out and Transport

Array cables are typically stored at either the manufacturer’s port facility or at the marshaling yard in pre-cut lengths to match the required cable routing. Once a string of foundations has been laid, the array cabling for those foundations is loaded onto the array cabling vessel. Array cables are typically stored and loaded onto vessels on reels, as the lift weights are not normally prohibitive at the comparatively short lengths involved. Otherwise continuous loading techniques may be employed, whereby the cable is spooled onto the vessel, as used for long export cable load outs.

Either an adapted cable barge or a specialist Dynamic Positioning (DP) cable installation vessel can be used to transport the cables to the site and perform the subsequent array cable installation work.

Installation

The cable is normally paid out from the stern of the vessel via a series of rollers and pulleys, to ensure a smooth transition onto the seabed, without exceeding minimum bend radii or incurring undue abrasions, etc. Once on site, the vessel is positioned adjacent to a wind turbine or substation structure and holds station either using dynamic positioning or a pattern of mooring anchors. A cable end is then floated off from the cable reel on the vessel, towards the nearby wind turbine structure and connected to a pre-installed “messenger line” already threaded through the J-tube. The cable is then pulled up the J–tube in a controlled manner with careful monitoring using the messenger line. This pull is typically performed using either a temporary hoist arrangement set up above the J-tube on the foundation or using a vessel-mounted crane. When the cable reaches the cable termination point, the pulling operation ceases and the cable joint is made.

Source: GL GH

Figure 3-26: *Normand Mermaid* DP Vessel Used for Array Cable Laying at the Thanet Project, UK

The cable is laid away from the first turbine structure towards the J-tube on the second. The cable installation vessel either moves under DP control or by hauling on its anchors while redeploying the anchor pattern as required. Cables are either laid temporarily on the seabed awaiting burial or buried simultaneously to laying. This decision largely hinges upon the day rate and mobility of the installation vessel, as the burial procedure will normally slow down a costly DP vessel considerably, while the speed and costs of an anchored barge will be much less impacted. If the cable is being buried simultaneously to its laying, then the installation vessel will usually be used to pull and control the plow or jetting rig.

Some cable laying ROVs include a cable spool and hence allow the cable to be both laid and buried independently of the vessel from which they are operated.

Choice of cable trenching methods is wide ranging and very dependent upon seabed soil conditions and the particular experience of the contractor involved. To date the majority of offshore projects have been located on sands, muds or other sediments and hence the commonest methodologies for cable embedment have been either plowing or jetting. In firmer soils some form of pre-trenching may be adopted, or in very hard or rocky areas it is usual to bury cables using concrete mats or rock dumping techniques. These approaches are summarized as follows:

- **Plowing:** As the term suggests, plowing involves pulling or towing a plow along the seabed, either from a vessel with sufficient bollard pull capacity, or, in relatively shallow waters, from a well-anchored vessel using winches. Plows provide a good, relatively low-tech solution in soft and medium soils provided there are minimal rocks, boulders, or other obstructions. The narrow, underwater plow cuts a trench and lays the cable within that trench in a single pass (see Figure 3-30). Unlike plows seen in agriculture, the trench is usually moreover a slit in the seabed without the soil being actively removed or turned over. This means that subsequent back-filling is not normally necessary as the slit will close up as the plow passes. The plow will usually be designed to pull itself into the soil and use skids or wheels to react the downward pull as well as for guiding it along the cable route.

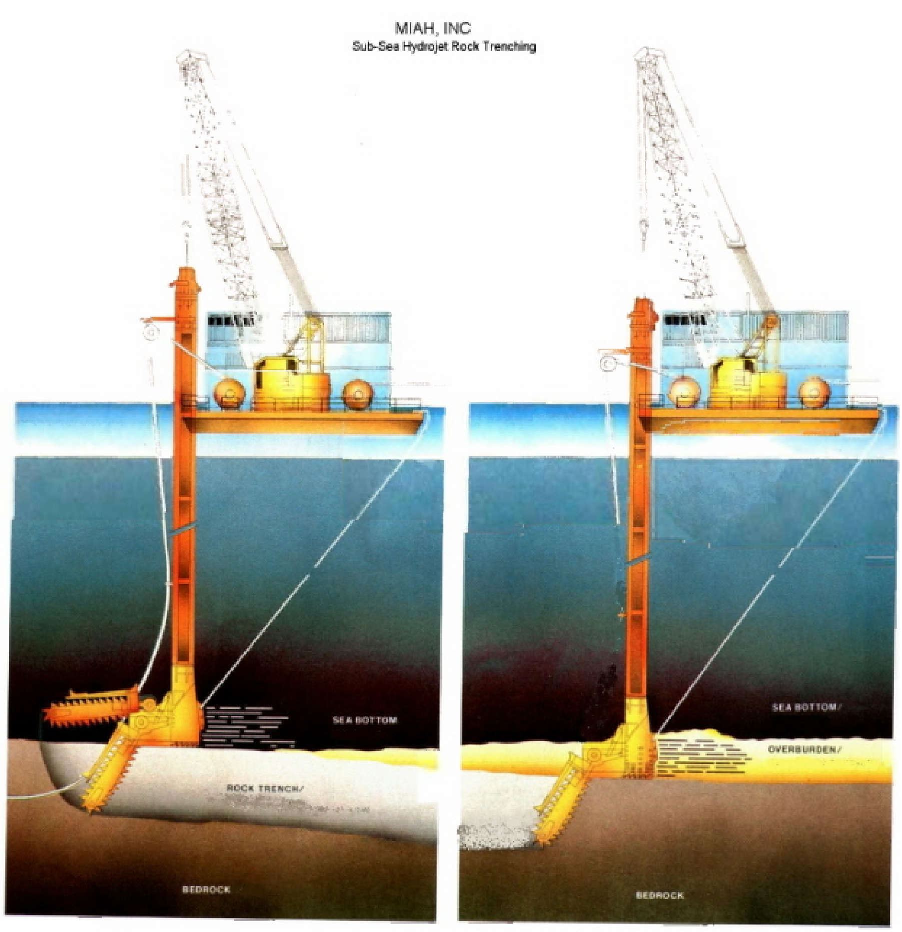
- **Jetting:** Generally jetting works well in loose, fine, granular soils, while cohesive soils respond better to plowing. Jetting relies on a series of high-pressure water jets to fluidize the local sediment and enable the cable to sink through the sediment to the required depth. The water jets are often arranged on a plow-like arm with the cable laid immediately behind the jets. Indeed, some cable trenching tools use a combination of plowing and jetting to achieve the required depths for a given pull force. Jetting lends itself well to self-propelled underwater vehicles, due to the reduced pulling forces required. Clearly, jetting tools require substantial umbilical cables from the vessel in order to provide power to the array of pumps required.
- **Pre-trenching:** Pre-trenching usually adopts a plowing method in soils where the soil is suitably firm or cohesive to prevent the trench re-filling as soon as the plow has passed. This may be a preferred solution if rocks or boulders are anticipated as the trenching and laying are performed as separate operations. More similar to an agricultural plow, back-filling will be required after the cable is laid in the pre-trenched route, for which further plow-like tools may be used to follow the original trench.

  In very hard soils or rock, pre-trenching may be performed by hydraulically-driven, underwater cutting wheels or chains, either mounted upon a self-propelled unit of some form or suspended from a barge (see Figure 3-27). However, given the slow speeds of these approaches, rock-trenching is normally only appropriate for relatively short cable runs. Furthermore, environmental consenting may restrict whether this option will be tolerated, and may lead to a requirement for the careful removal and disposal of excavated material.
- **Burial:** The oil and gas industry has pioneered various means of underwater burial of pipelines, the technology of which applies well to sub-sea cable burial. Perhaps most notable in this context is the use of fall-pipe vessels for accurately positioning rock to cover such underwater utilities. Fall-pipe vessels use long, extendable pipes to pass rocks vertically through the hull of the vessel to a few meters above the seabed. Here an ROV attached permanently to the end of the pipe can be used to accurately position the pipe and hence the fall of the rocks. This approach is significantly less wasteful than simple over-the-side dumping methods, as the rocks can be located very accurately, even in high current situations.

  Burial can also be achieved through the use of rock mattresses. Large mattresses of rock can be assembled onshore by encasing rock in netting or casting concrete onto rope lattices and subsequently lowering the mattress into position over the cable offshore.

When the cable installation vessel nears the J-tube on the second wind turbine structure, the cable end is taken from the reel and made ready for pulling up the second J-tube and the pulling operation is repeated in the same manner as was employed at the first J-tube. It is normal for some excess cable to be laid on the seabed close to the second J-tube to accommodate burial and provide a degree of over-length allowance. Clearly, the cable laying vessel and burial spread cannot proceed over or through the foundation and hence it is common for the cable route to appear to “miss” the foundation before turning suddenly towards it.

If the burial was not conducted in conjunction with cable laying, a post-lay burial spread will be required to complete the work when schedule and weather conditions allow. These post-lay plow or jetting spreads comprise a vessel (often much cheaper than the cable laying vessel) and some form of cable burial ROV. Self-propelled, tracked cable burial ROVs are well suited to such post-lay burial works, although towed equipment may also be used. The ROV may have to deploy temporary ramps to allow itself to track safely astride the cable without causing damage. Once in position over the cable, the burial process can commence in a similar fashion to the plowing or jetting techniques outlined above.



Source: Miah Inc

Figure 3-27: Miah Rock Trenching Arrangement

The target burial depths vary depending on risk assessment of damage to the cable at the particular site, but can be as little as 1 m or up to around 3 m. The choice of how deep to embed the cable is primarily dependent on the likelihood of fishing, anchoring, or other sources of potential external aggravation coupled with the likelihood of subsequent cable exposure due to current and wave-induced mobile seabed conditions.

When the main burial operation of each array cable has been completed, it is normally necessary to revisit the exposed areas of the cable lying on the seabed surface close to each of the J-tube exit points, as the plow or jetting spread will not normally be able to gain access close to the foundations. There are four potential options to protect these awkward end sections of cable as outlined below:

- **Cable armoring:** Firms such as Tekmar produce specialist cable protection systems which are either threaded onto the cable during laying or clamped over the exposed lengths afterwards. These will typically comprise hinged sections designed to maintain a degree of flexibility while protecting the cable from crush loads, wear, and excessive bend radii. These may be additionally beneficial if large rocks are to be used for scour protection around foundations.

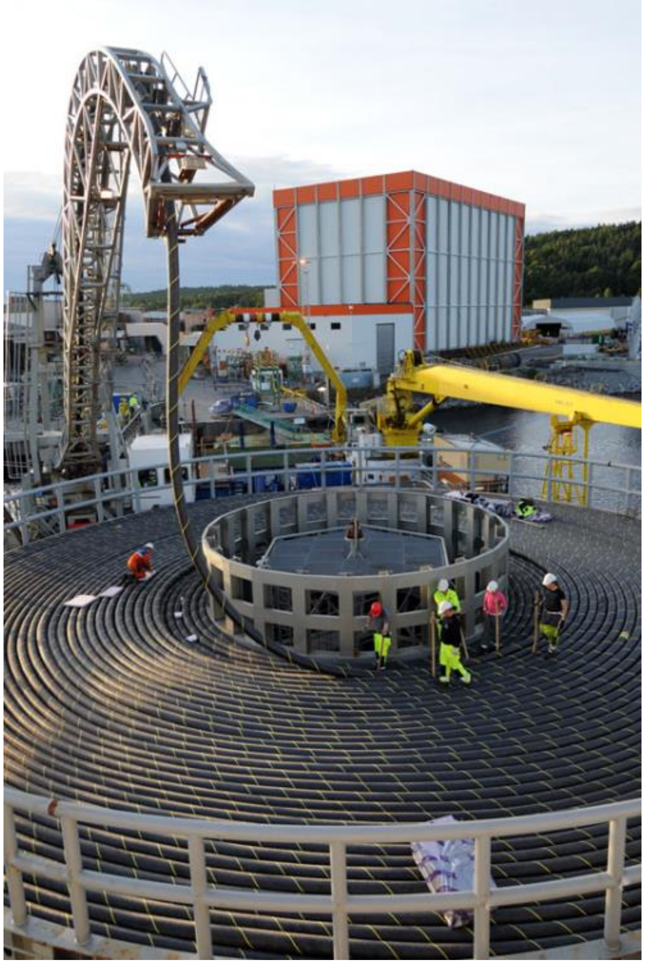
- **Manual burial:** Divers may be deployed with hand-held jetting lances or other excavating equipment in conjunction with air lift devices to manually excavate trenches close to the J-tube ends of the cable. This is subject to the ground conditions being suitable.
- **Rock dumping:** Use of fall-pipe or side-dumping vessels to dump rock over exposed areas of cable. This may be conducted as part of wider scour prevention works.
- **Fabricated coverings:**
  - **Pre-fabricated:** Rock or concrete mattresses may be fabricated onshore and then lifted and placed over the cable sections to protect the cables. This methodology is sometimes supplemented with the use of sandbags to stabilize the edges of the mattresses.
  - **Post-fabricated:** Empty grout bags are placed over the lengths of cable and then inflated with structural grout once on place. The grout then cures to provide a molded cover protection system for the cables. This approach requires diver assistance.

Subsea Export Cable

The primary difference between export cables and array cables are the lengths, diameters, and weights involved. Export cables are typically in excess of 200 mm in diameter with weights exceeding 80 kg per meter and often sufficient length to span the entire distance from the project to the shore. Due to the continuous process for fabricating the cable, the maximum cable length is limited by the spool or vessel carrying capacity. For export routes which exceed the maximum length of cable on a spool, joints will need to be made to stitch multiple sections of cable together. Due to the significant diameters and weights involved, bending radius and support during laying are even more critical than for array cables. Clearly, the vessels and plant involved in export cable laying and burial are therefore significantly larger than those required for array cable works.

Load-out and Transport

The cable is typically wound onto the installation vessel at the manufacturer's facility due to the extreme weight of the fully laden spool or cable tank. The weight also prevents the use of feeder vessels and hence the installation vessel must be used to transport the cable to the starting point of the installation works. On the vessel, the cable is stored in either a static cable tank or a rotating cable carousel. Cable tanks use a complex system of pulleys and guides to lay the cable in a layered spiral fashion within a large, circular, static container and retrieve it without placing undue torsion on the cable. Cable installation vessels are also equipped with cable handling equipment to control the tension during the cable lay and to provide holdback to control the rate of cable pay-out.



Source: Photo at Sheringham Shoal taken by CHPV and supplied by Scira Offshore Energy

Figure 3-28: Export Cable Load-Out for the Sheringham Shoal Project, UK

Installation

There are two potential routes by which the export cables can be installed:

- Installing the cables from the wind farm to shore (often required if directional drilling underneath sensitive inter-tidal regions is required); or
- Installing the cables from shore to the wind farm (a common approach if the route is straightforward).

Installation and burial of export cables is conducted using the same plowing or jetting techniques as those discussed above for the array cables, again with the option for either simultaneous lay and burial or post-lay burial.

As for array cable laying, the export cable installation vessel is likely to be a DP vessel (see Figure 3-29) or an unpowered barge using a mooring pattern of anchors. The higher day-rate DP vessels benefit from the speed of being able to self-position, while the lower day-rate unpowered barges rely on up to eight anchors and associated anchor handling tugs to control position and haul against. The unpowered barges have the added benefit that they are typically flat bottomed, allowing them to operate in very shallow waters and, in some circumstances, to safely 'ground' on a receding tide.

Source: London Array website. VSMC vessel the Stemat Spirit. Photo: Carel Kramer

Figure 3-29: Stemat *Spirit* DP2 Cable Laying Vessel

Clearly, the exact approach adopted for export cable installation will depend heavily upon the cable route and any technical or environmental sensitivities along that route. However, the following points outline the basic procedure typically adopted:

- The cable installation vessel arrives at a location close to the shore landing point, approaching the shore near high tide.
- The cable end is passed from the cable installation vessel and connected to a tow wire connected to an onshore winch. The cable end is then floated off from the vessel and towed towards the shore. When the cable end reaches the beach, a series of portable roller sets are laid on the beach to reduce friction and allow the cable end to be pulled up to the cable onshore jointing chamber.
- The cable end is then secured at the joint transition pit.
- If simultaneous lay and burial is to be adopted, the subsea cable plow is deployed either on the seabed, or, depending upon the terrain, on the beach or inter-tidal region. The cable installation vessel slowly moves away from the shore, establishing catenaries in the export cable and plow tow lines.
- The simultaneous lay and burial of the cable commences with the vessel moving away from the shore. Figure 3-30 shows a cable plow burying cables at the shore being pulled towards the host barge, which has been deliberately grounded on the beach before re-floating at high tide and moving away to the wind farm, simultaneously laying and burying the subsea cable.

Source: www.vsmc.nl. Photo: Carel Kramer

Figure 3-30: Visser & Smit Marine Contracting *Sea Stallion 4* Subsea Cable Plow Burying Cable at the Shore

- The plow parts a narrow trench in the seabed, typically burying the cable to a depth of 1-3 m depending upon seabed conditions.
- The cable installation vessel will normally continue past the offshore substation, stopping when the plow is as close as possible. The subsea cable plow is then recovered onto the deck of the cable installation vessel.
- With the plow recovered on deck, the cable end is floated off from the vessel towards the substation structure. A roller quadrant is often suspended from the crane on the cable installation vessel during this cable handling operation to facilitate safe and careful handling.
- At the substation, the cable is connected to the end of the messenger line exiting the J-tube's bell-mouth.
- The cable is then pulled up the J-tube in a controlled manner with careful monitoring of cable tension and radius during the complete operation.
- When the cable reaches the cable termination point, the pulling operation ceases and a strain restraint is connected to the cable end.
- Clearly this installation procedure leaves a section of cable unburied from the point of subsea plow recovery to the J-tube bell-mouth. This section of cable is buried at a later date using a post-lay burial ROV, rock dumping or other remedial protection, usually as part of the scope of work for the array cables.

In some cases, environmental consents or the shoreline terrain require that directional drilling be used to pass the export cable(s) underneath difficult or sensitive areas. Under such circumstances the cable installation procedure outlined above will need to be adapted accordingly.

Cable Protection

Where the soft overburden over rock is of inadequate thickness to embed cabling, or if no sediment exists in which the cable may be buried, it may be necessary to adopt alternative cable protection methods. One technique is to lay concrete mats, or other geo-fabric based solutions over the cable. This affords the opportunity to design easily installed custom solutions and is particularly useful for complex areas like other cable or pipeline crossing. Many companies such as Subsea Protection Systems (SPS) provide a range of solutions to protect cables and allow cable crossings.

Offshore Substation

The majority of offshore projects to date have included at least one offshore substation, although the electrical losses from small projects located close to an onshore substation may not merit this additional infrastructure. It is common for the offshore substation(s) to be installed early on in the installation schedule so that further electrical installations can continue in parallel with foundation and turbine installation.

Foundation Installation

Foundations used for substations are generally jackets or monopiles, although concrete gravity structures have also been used in the past. Installation will be undertaken in a similar manner to the wind turbine foundations, although sometimes a vessel with greater lift capacity is required, as the substation foundation may be heavier than those used for the turbines.

Topside Load-out

The sub-station topside is normally installed as a complete unit, although a modular approach is also feasible. In either case the topside is usually assembled at a port facility close to the wind farm site. Fabrication is likely to be undertaken some way from the quayside and therefore it is usually necessary for the substation topside to be transported to the quayside using Self-Propelled Modular Transporters (SPMTs) prior to being lifted onto the heavy-lift vessel. Due to the very heavy lifts and the limited number of trips required, use of a feeder vessel is not appropriate for offshore substation installation and hence the installation vessel itself will be used to transport the topside to site.

Topside Installation

A heavy–lift crane vessel installs the sub-station topside directly onto the sub-station foundation, as shown in Figure 3-31. This can be done in a single lift or in separate lifts of deck and sub-modules. Due to the very heavy lifts involved (often well in excess of 1,000 metric tons), it is normal for a sheer-leg or semi-submersible crane vessel to be used, considerably limiting the sea-states in which this critical activity can be performed. After placement of the topside, fastening and welding operations are carried out by crews accessing the structure by work boats.

Source: London Array website. London Array Limited.

Figure 3-31: Substation Topside Installation at the London Array Project, UK

3.3 Innovative and Future Trends in Installation Methodologies

A primary aim of this study is to consider new and emerging approaches to installation, whether brought about by innovative component design (such as a new type of foundation), or an alternative approach to installing existing technology. This section discusses some of these emerging approaches to plant and installation. The installation modeling discussed in Section 6 is intended to capture the essence of some of these approaches to allow the user of the Installation and O&M LCoE Analysis Tool to evaluate the impact on project economics.

3.3.1 Floating Wind Turbines

Overview

The coming few years will see large European offshore wind farms built in unprecedentedly deep waters, in particular within the German sector of the North Sea. The cost of the support structures needed, in terms of both fabrication and installation, are significantly higher than the monopiles and Gravity Base Structures (GBS) used for the offshore wind farms currently under construction. As depths increase further, the costs of such support structures increases similarly and it is apparent that costs must become prohibitively expensive at some point if the same technology is to be used. However, as depths and costs increase, alternative options for supporting the turbine become viable, including floating support structures.

Utilization of floating support structures will deliver a number of important benefits, principally:

- Greater choice of sites & countries, including the Mediterranean (France, Spain, Italy), Norway, U.S. (East and West coasts) and East Asia (China, Japan, Korea);
- Consistency of hull design in all water depths;
- Cost potentially similar to fixed structures in medium depths, although this remains to be demonstrated in practice;
- Less dependence upon soil conditions;
- Greater flexibility of construction & installation procedures; and

- Easier removal/decommissioning.

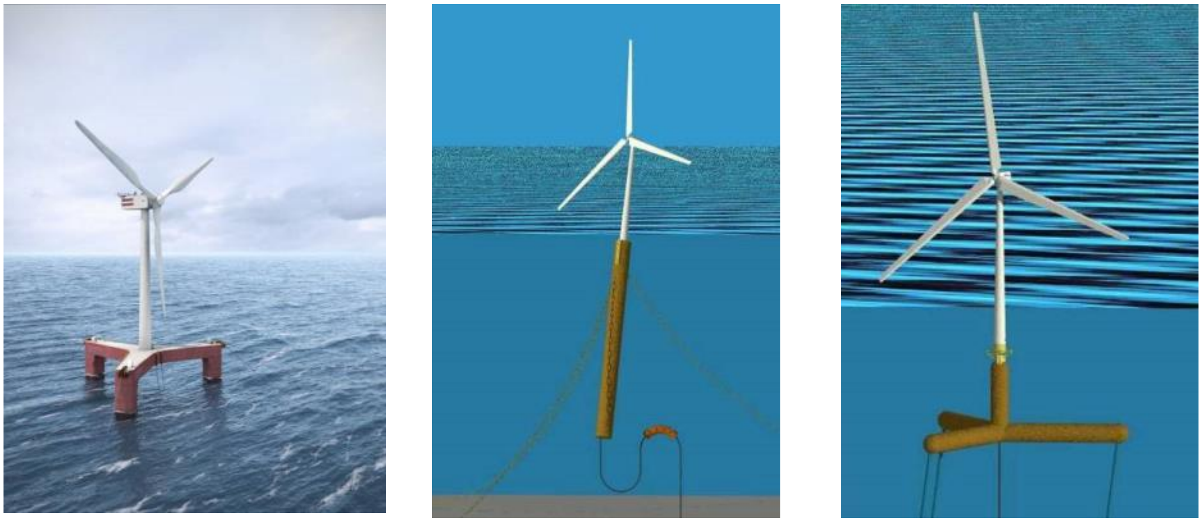
However, the dynamics of floating foundations introduces a number of new challenges, including:

- Minimization of turbine- and wave-induced motion;
- Additional complexity for the design process, including understanding and modeling the coupling between the support structure and the wind turbine (moorings & control);
- Electrical infrastructure design and costs, in particular the dynamic cable and underwater interconnectors; and
- Construction, installation, and O&M procedures.

A floating wind turbine support structure can be broken down into the following systems:

- Structure (hull): maintains buoyancy and structural integrity;
- Mooring: connects the floater to the seabed, typically chain or cables;
- Anchoring: attaches the mooring lines to the seabed;
- Electrical cable: capable of withstanding the movements of the structure while exporting power.

There are three primary classes to floating structures; the spar, the tensioned-leg platform (TLP) and the semi-submersible structure, as illustrated in Figure 3-32. To date only the spar and semi-submersible approaches have been demonstrated at full-size offshore projects.



Semi-submersible Class

Spar Class

Tension-Leg Platform (TLP) Class

Source: Semi-submersible (left): Courtesy of GustoMSC; Others: GL GH

Figure 3-32: Floating Support Structure Classes

Of these, all are well proven within the oil and gas industry and hence are both technically and practically viable. Each class has different characteristics and strengths. The spar and jacket-type floating foundations have the benefit of existing, full-scale wind turbine demonstrator projects, while the tensioned leg and jacket types can be used in shallower waters than the spar (in some cases down to 50 m or less) and, for the tensioned leg platform foundation, a lightweight, elegant design should be achievable in time.

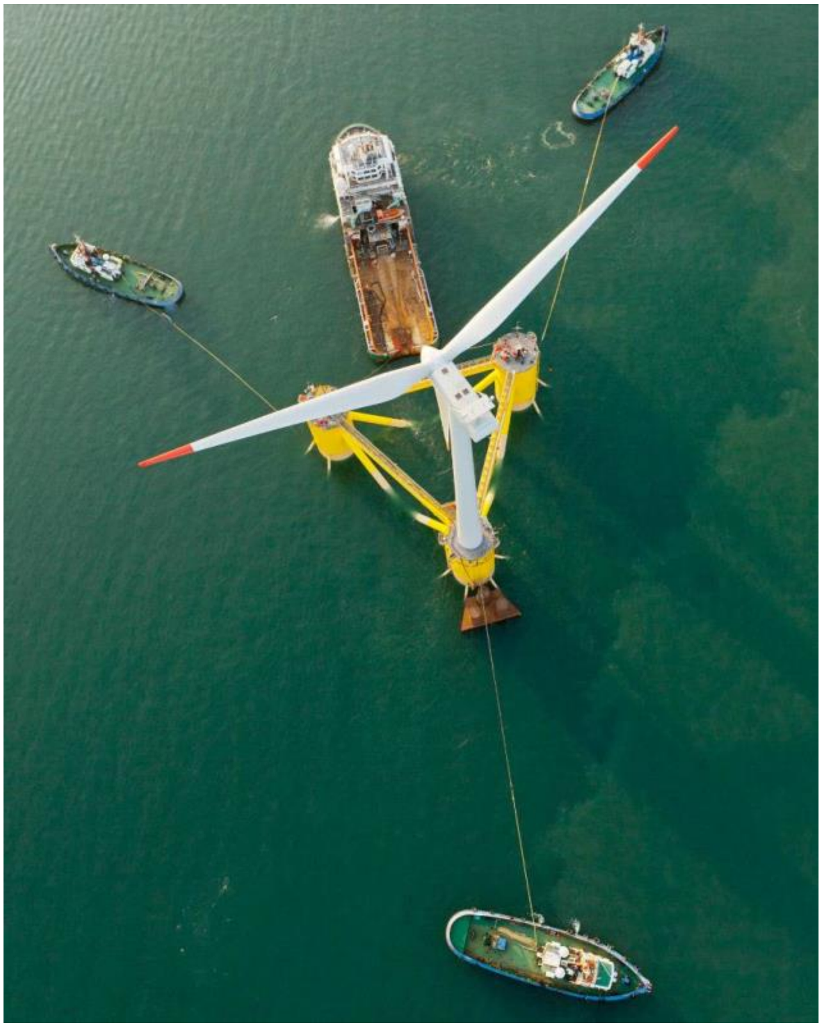
Two, full-size floating demonstrator turbines have been installed offshore to date, namely Statoil's spar-class "Hywind" concept off the coast of Stavanger in Norway and Principle Power's semi-submersible class "WindFloat" demonstrator near Povoa de Varzim in Portugal. A number of scaled demonstrators have also been installed, including the Sway floating spar-based concept, in Norwegian waters, and the Blue-H TLP concept in Italian waters.

Installation

Due to the immaturity of floating wind technology, there is very limited experience with installation techniques. The two full-scale floating turbines which have been installed to date have been towed to site, pre-assembled on their respective foundations, whereupon they were connected to anchor lines and dynamic power cables.

Source: Statoil. Photo: Øyvind Hagen/Statoil

Figure 3-33: Float-out of Hywind Spar-class Foundation and Siemens 2.3 MW Turbine



Source: Principle Power Inc., as reproduced by the Green Architecture and Building Report

Figure 3-34: Principle Power's Windfloat Demonstrator being Ballasted and Towed to Site

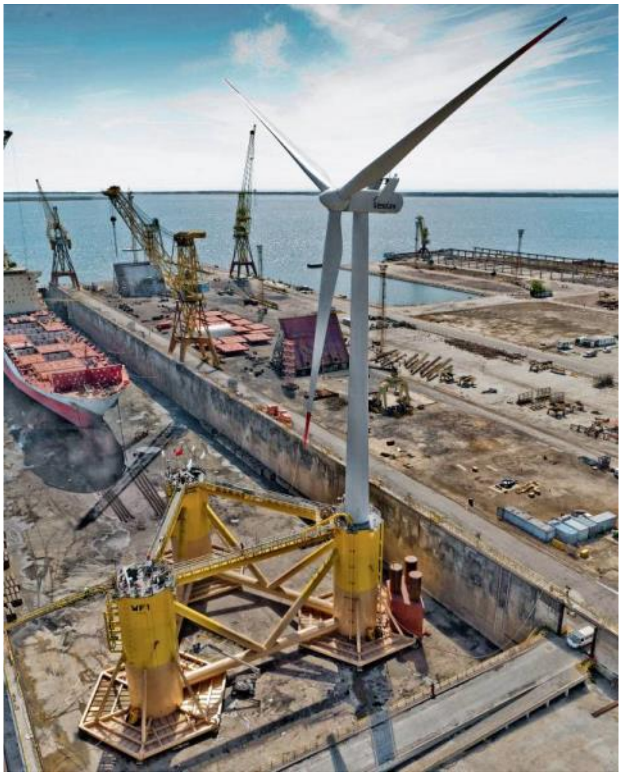
A key factor when considering the installation of floating foundation concepts is that most jack-up vessels are unlikely to be able to operate in the water depths required. Therefore piecewise installation of turbine components on site is no longer an option due to the motions of both the installation vessel and turbine. With this in mind, there are three broad approaches to transporting and installing floating turbines:

- **Tow both foundation and turbine out to site pre-assembled in a vertical orientation**. This is the approach adopted for both full-scale demonstrators installed to date. This approach is ideally suited to semi-submersible foundation concepts due to their inherent stability and limited water depth requirements. Meanwhile, spar-type foundations require very deep, sheltered waters in which to assemble the turbine (such as a Norwegian fjord). Tension-leg Platforms will require additional stabilization or ballasting to enable such a pre-assembled tow-out approach.
- **Tow or transport the foundation out to site and install a pre-assembled turbine onto it**. This approach may circumvent some of the issues associated with near-shore, deep-water assembly of a turbine on a foundation as well as some of the difficulties of towing the combined structures to site. Furthermore, some

TLP designs may enable this approach to be adopted without the need for temporary support or ballasting during tow-out. However, the installation would nevertheless require a sheer-leg crane vessel or equivalent to install the pre-assembled turbine on the floating foundation. This operation would require very benign conditions, although this requirement may be mitigated somewhat by the development of a system to mechanically "clamp" the foundation to the vessel during this critical operation, thereby ensuring that motion is common to both structures.

- **Tow both foundation and turbine out to site pre-assembled in a near-horizontal orientation.** This approach has been adopted by Idermar for the deployment of three floating Spanish meteorological masts. The approach uses buoyancy tanks (and potentially ballasting) to maintain a spar-type structure in a near-horizontal orientation while towing out to site, thereby significantly reducing the depth requirements at the load-out port. GL GH is not aware of any concept developers currently considering this option for turbine installation due to the considerable loads which would be imparted to the turbine tower and the complexities of assembling the structure and implementing the buoyancy required.

An additional factor which should be considered when assessing the approach to installation is the method by which the floating foundation structures are manufactured. The semi-submersible and, potentially, the TLP concepts are ideally suited to fabrication in dry dock facilities, due to their limited draft of 10-20 m or so. This avoids the need for a very heavy lift over the quayside and potentially allows the turbine to be installed on the foundation prior to flooding the dry dock, removing all dynamic lifts during assembly. Figure 3-35 shows the assembled Principle Power semi-submersible concept in a dry dock prior to floating.



Source: Principle Power Inc., as reproduced by the Green Architecture and Building Report

Figure 3-35: Principle Power's WindFloat Foundation and Vestas V80 Turbine Pre-assembled in a Dry Dock

3.3.2 New Fixed Foundation Concepts

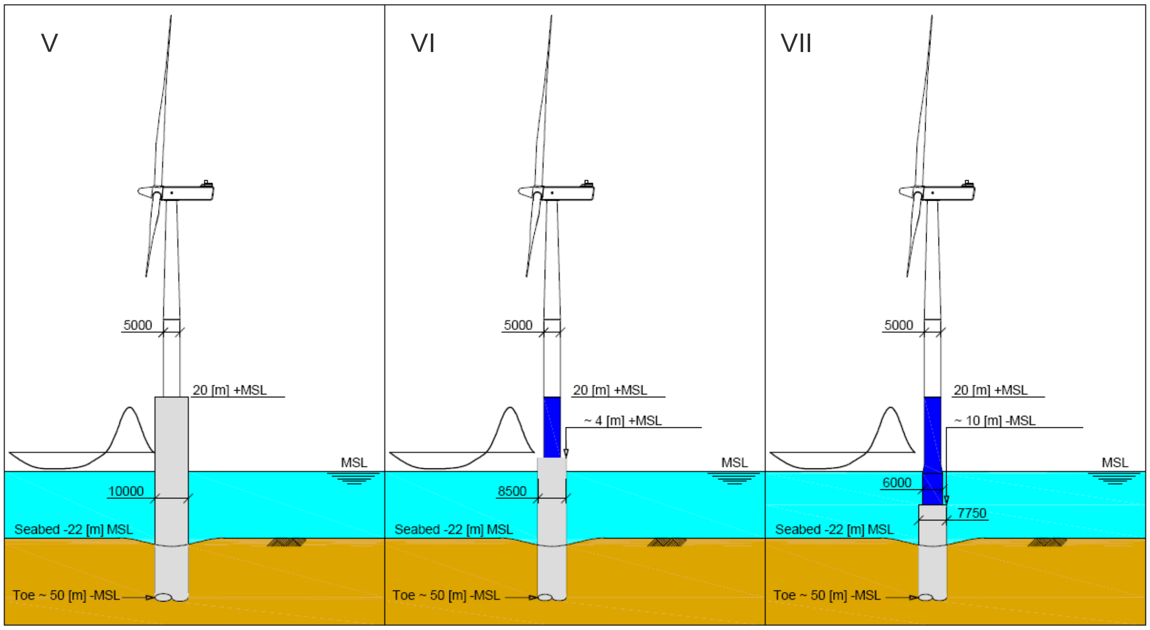
There are a number of variants to the common foundation types discussed in Section 3.2.5 currently being considered and trialed within the offshore wind industry. Some of these are discussed within this section, although it should be noted that the concepts included here are not exhaustive.

Concrete Drilled Monopile

Ballast Nedam, a Dutch offshore contractor with some offshore wind experience, has proposed a drilled concrete monopile (see Figure 3-36 and Figure 3-37). The primary benefits of this approach are the potential savings in raw material costs, while simultaneously opening up the fabrication to many additional providers, previously limited by the steel fabrication methods required for the production of traditional monopiles. Limited corrosion or need for cathodic protection are additional benefits.

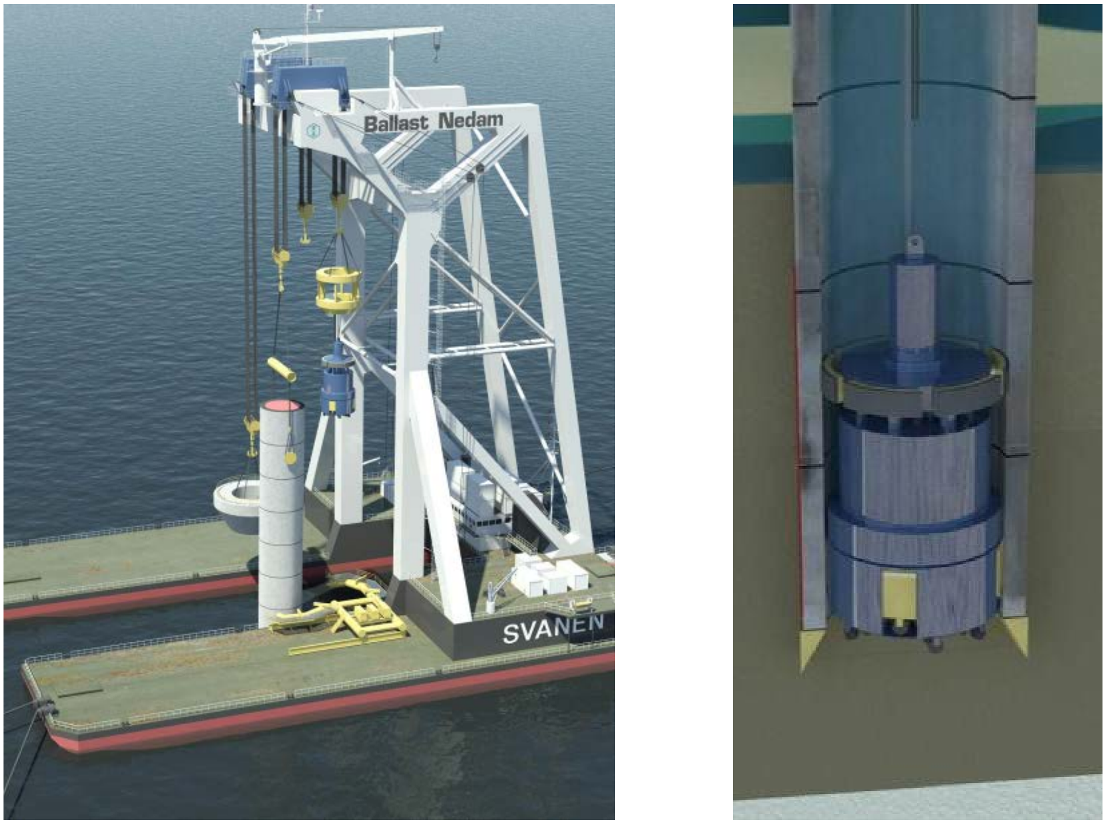
Ballast Nedam is proposing to install these foundations using its bespoke vessel *Svanen* ("Swan") (Figure 3-37). *Svanen* was originally constructed to build the Oresund Bridge connecting Denmark and Sweden. It has worked on at least one further bridge contract; however, its unusual shape means demand for its services is comparatively limited.

Svanen has been used to install steel monopiles at a number of sites and its crane is capable of lifting much heavier weights. The geometry of the twin barges on which she is built means that jackets or tripods cannot be installed due to their width. Conversely, there are only a limited number of vessels that could install concrete drilled piles in a cost-effective manner, with *Svanen* possibly being the only such vessel.



Source: ©Ballast Nedam, European Offshore Wind Conference Stockholm 2009

Figure 3-36: Ballast Nedam's Concrete Drilled Monopile



Source: ©Ballast Nedam, European Offshore Wind Conference, Stockholm 2009

Figure 3-37: Installing Concrete Drilled Monopile – *Svanen* (vessel) and Detail of Drilling Plant

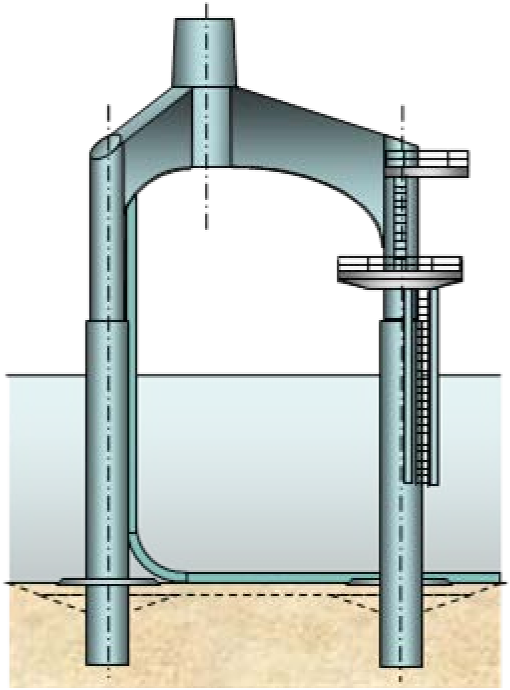
As with a drive-drill-drive approach using traditional steel monopiles (see Section 3.2.5), Ballast Nedam's approach involves the following key steps:

- Float-out of the concrete monopiles to the installation vessel (*Svanen*);
- Use of the installation vessel crane to up-end the monopole and place in a guiding frame;
- Lowering of the monopile to the seabed and the drilling rig inside the monopile;
- Drilling to the required depth at a diameter larger than that of the monopole;
- The monopile "follows" the drill under gravity;
- The annulus or void due to the over-size hole is filled with a self-hardening drill-fluid.

While it is an un-tried offshore wind farm foundation type, the drilled concrete monopole utilizes several existing technologies, in a reasonably conventional manner and, as such, has a relatively low technical risk in comparison with many new concepts. However, the high investment cost of the drilling equipment would require that a significant number of foundations would probably need to be installed before the investment became economically attractive.

Tri-piles

In this design, three foundation piles are connected via a transition piece to the turbine tower with the transition piece being located above the water level. BARD has patented a specific version of this concept which consists of a transition piece with three pins that slot into the three pre-installed piles. A design objective was to balance the weight of these four components (three pin-piles and the bridging structure) to ease the challenges of handling and installation. Note that the first offshore wind turbine to be constructed, a 220 kW Windworld unit at Nogersund in Sweden in 1990, was constructed on a tri-pile type design.



Source: GL GH

Figure 3-38: Generic Tri-pile Foundation Design

Tri-piles may be installed in much the same fashion as space-frame structures (jackets and tripods) as discussed in Section 3.2.5. Likewise, they can theoretically be installed with pre- or post-piling methods, although only pre-piling has been used with these structures to date. Figure 3-39 shows some fabricated tri-piles at the Cuxhaven Steel Construction yard in Germany awaiting installation at the BARD Offshore 1 project in the German North Sea. Notice the conical feet for guiding the foundation into the pin-piles, as well as the black, rubber grout seals for preventing the liquid grout from flowing out prior to curing.

Source: GL GH, courtesy of Cuxhaven Steel Construction (CSC)

Figure 3-39: Tri-pile Foundations at Cuxhaven Steel Construction Awaiting Installation at BARD Offshore 1 in German North Sea

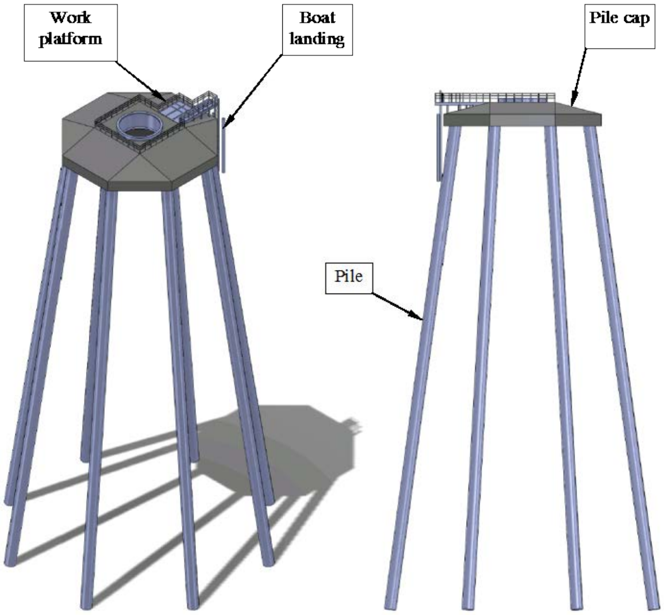
Battered Pile

This foundation design solution comprises a reinforced concrete pile cap sitting on battered (inclined) driven steel piles. The primary advantage of this foundation type is its ability to function in very soft ground conditions, where ground stiffness would otherwise require excessive monopile dimensions. The loads from the turbine tower are transferred through the pile cap into the piles. The pile cap resists mostly bending moments and shear forces, while the piles resist mostly axial forces, though the latter are also subject to some bending moments. This foundation design would generally be used in shallow sheltered waters, hence the wave loading on the structure accounts for a very small proportion of the total loading; in this respect the foundation is essentially an onshore foundation, the main difference being that the foundation is to be constructed from an offshore perspective rather than for land use.

There are multiple alternative ways in which these foundations may be installed, but whichever is adopted it is likely to be a time-consuming process due to the large number of offshore operations required. Some potential approaches are outlined as follows:

- Installation of the battered piles:

  - Use of a pile-guide template during pile driving. Due to the raked angle of the piles, the template must either be disassembleable for removal or left in situ. This approach would enable installation from a floating vessel.
  - Use of a piling leader, suspended by crane to enable the correct rake on each individual pile. This will avoid the use and removal of a complex template, but would require the piling leader to be carefully positioned for each pile and may heavily restrict the sea-states in which installation can be progressed, assuming a floating vessel is used.
- Installation of the pile cap:
  - In-situ casting of the pile cap. This will require considerable efforts to install the necessary formwork and reinforcing steelwork, but should provide reasonable flexibility and tolerance for imperfections in the pile installations.
  - Pre-fabricated or modular pile cap lifted into place and then grouted or welded. Due to the raked piles, this would either need to be a modular design or would require additional in-situ casting around the piles.
  - Construction of a circular, sheet-piled cofferdam around the battered piles, into which sand is compacted. The pile cap is then cast in situ using the sand as support and the cofferdam as the formwork for the sides. Clearly this approach assumes shallow waters.



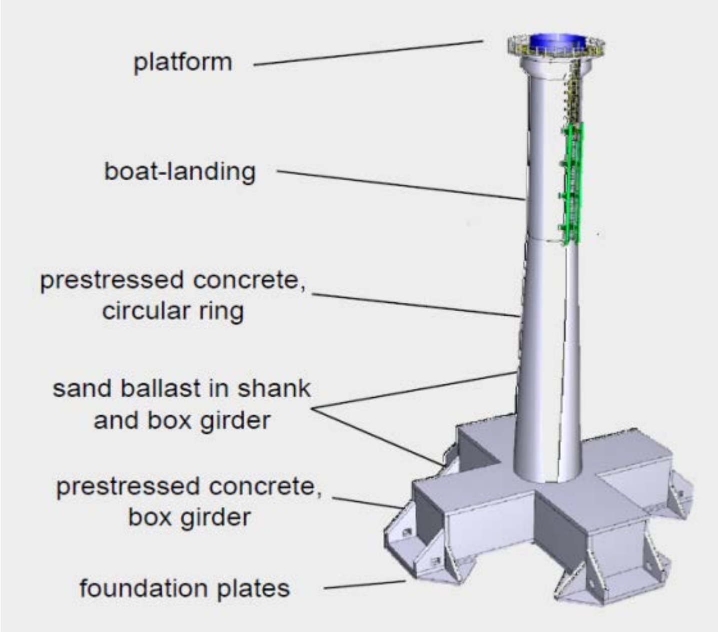
Source: GL GH

Figure 3-40: Example of a Typical Battered Pile design

In 2010, 34 Sinovel 3 MW turbines were installed on battered pile foundations in the shallow waters of the Donghai Bridge project in China.

Novel GBS Concept

Strabag, an Austrian construction firm with a majority stake in Stuttgart-based Ed. Züblin AG, has proposed a GBS derivative consisting of a concrete “X” or “Y” lying on the seabed, supported on pads at the ends of the arms, as shown in Figure 3-41. The Arkona-Becken met mast was installed on a “Y” configuration of this foundation type; however, at the time of writing it has not been utilized in support of offshore wind turbines. In 2010 Strabag began the manufacture and load-testing of a scaled prototype of the foundation in Cuxhaven, Germany.



Source: Strabag Offshore Wind “The Base of Power” Presentation at Offshore Wind Energy in Ireland, Dublin, 2010

Figure 3-41: Strabag / Züblin GBS

The installation methodology proposed by Strabag requires a unique, new-build installation vessel, for which the keel has yet to be laid. The proposed vessel is based on a twin-hull semi-submersible design, large enough to transport the concrete gravity foundation and pre-installed turbine supported vertically between the hulls. Additional stability during final placement of the foundation and turbine is performed via ballasting of the vessel and the use of underwater jacking legs on the vessel hulls.

Source: GL GH, courtesy of Strabag Offshore Wind

Figure 3-42: Strabag Installation Vessel (left) and Prototype GBS Foundation (right)

There is also a requirement for significant civil infrastructure to support the fabrication and load-out methodology. In general, the up-front investment necessary to support this technology requires there to be long-term serial production of several hundred foundations in the same locality over an extended period.

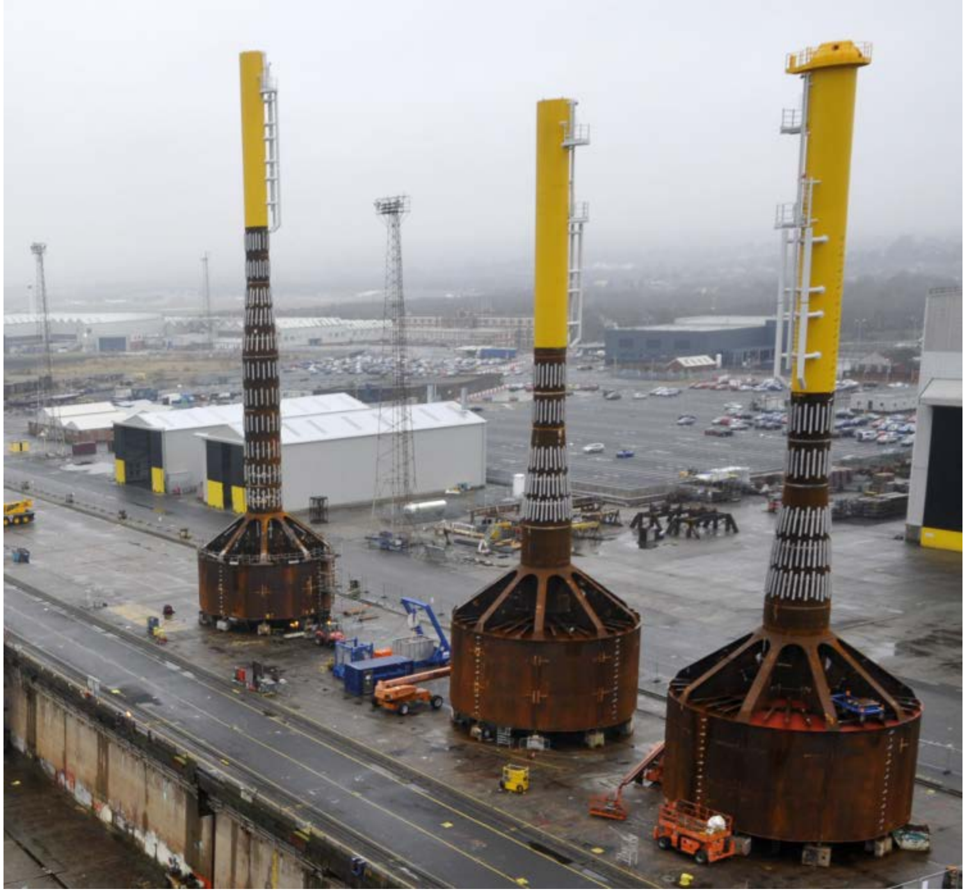
In early 2013 it was announced that Strabag was postponing plans to invest in further developments in its GBS foundations, fabrication yard, and installation vessels until further notice due to uncertainties in the future of offshore wind in Germany [16].

Offshore Wind Accelerator Foundations Innovators

In addition to the solutions mentioned above, the UK Carbon Trust has recently published the results of its Offshore Wind Accelerator (OWA) [17] [18] Foundations Competition which began in 2008. The Offshore Wind Accelerator Foundations Competition aimed to identify and develop new wind turbine foundation concepts to significantly reduce capital and installation costs for future wind farms. The OWA has taken forward four of these concepts into a detailed design phase which will consider fabrication, installation and transportation. These concepts are briefly discussed below.

Universal Foundations: Suction Bucket Monopile

The Suction Bucket Foundation by Universal Foundations combines the main aspects of a gravity base foundation, a monopile, and a suction bucket. It is said to be “universal” in that it can be adapted for a wide range of site conditions. Homogeneous deposits of sand and silts, clays and layered soils are all suitable strata for this foundation. It is claimed to be suitable for water depths of 30-60 m. The principle relies on the pressure of the water and sediment to bury the “upside-down bucket” and hold the foundation in place. Water jets mounted inside the suction bucket allow the upper layers of sediment to be fluidized and hence leveled during installation. Once installed, the foundation utilizes lateral earth pressure and vertical bearing capacity to resist loadings.



Source: GL GH, courtesy of Universal Foundations

Figure 3-43: Suction Bucket Foundations for Dogger Bank and Firth of Forth Met Masts

The installation process is expected to take fewer offshore operations and require smaller vessels and equipment. The foundation can be towed to site (as was adopted for the Horns Rev II met mast) and there is no piling required, considerably reducing noise. Moreover, it should require less scour protection, and decommissioning of the whole structure will be easier. The installation process harnesses the reduced pressure in the underside of the bucket to create a downward force.

Given that these suction buckets may be floated out and do not require piling, much of the requirement for large vessels with heavy lift capabilities may be avoided. At the time of writing, Fred Olsen United A/S is installing two Universal Foundations to support met masts at the Dogger Bank offshore zone in the UK, on behalf of project developer Forewind and a further met mast foundation at the Firth of Forth zone in the UK, on behalf of project developer Seagreen (see Figure 3-44). Other suction bucket foundations have been utilized for a number of demonstrations, specifically:

- Wind turbine at Frederikshavn, Denmark;
- Horns Rev II met mast; and
- An unsuccessful attempt to install a near shore Enercon demonstration turbine at Hooksiel in North Germany.

Source: DONG presentation at Hamburg Offshore Wind 2009

Figure 3-44: Suction Bucket Foundation

Furthermore, at the time of writing, Fred Olsen United A/S is installing two Universal Foundations to support met masts at the Dogger Bank offshore zone in the UK, on behalf of project developer Forewind and a further met mast foundation at the Firth of Forth zone in the UK, on behalf of project developer Seagreen.

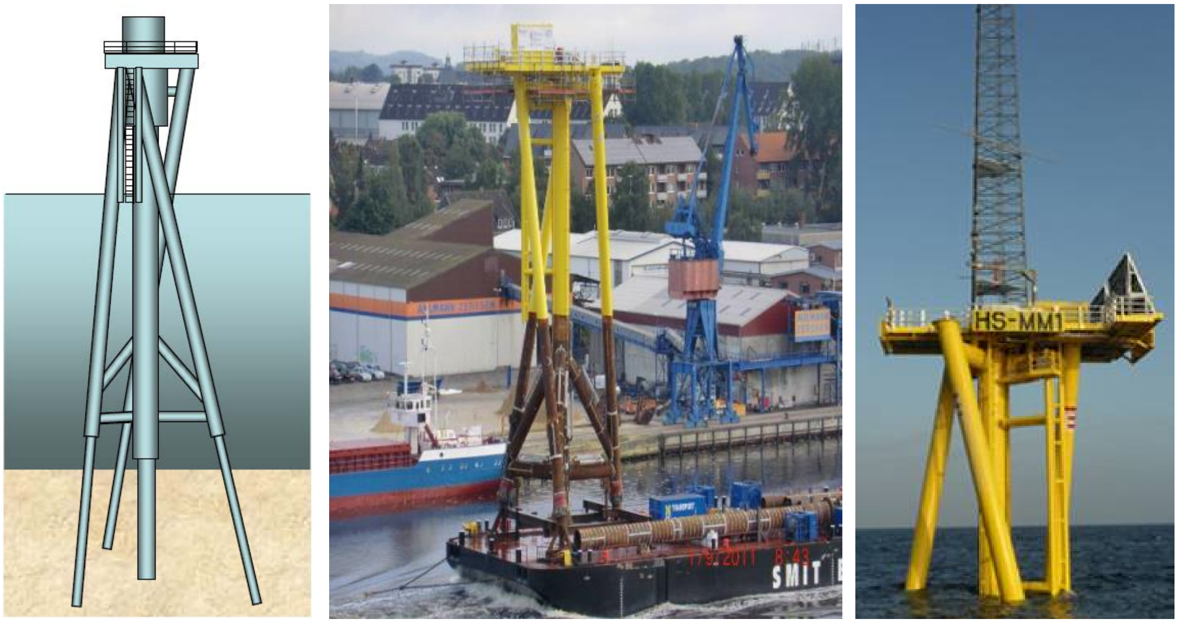
The same principle may also be applied in the form of space-frame foundations with suction caissons instead of pin piles. Although this concept is at a relatively early stage of development for wind turbines, it has been demonstrated for other offshore structures including the Norwegian Draupner E, unmanned oil and gas platform in the North Sea, which survived a “Monster Wave” of nearly 26 m in height in 1995.

Keystone Inward-battered Guide Structure (‘Twisted Jacket’)

Keystone Engineering (U.S.) has proposed the Inward-battered Guide Structure or ‘Twisted Jacket’ concept shown in Figure 3-45. Three supporting legs are angled around a central pile in a twisted configuration with a view to improving installation times. Installation times are improved given that the installation vessel does not need to readjust its location during the installation of the structure. In addition, no driving template is required, due to the post-piling approach, and the reduced foundation footprint with respect to traditional jacket designs may lead to improved utilization of deck space, increasing the maximum capacity per installation vessel.

Installation is performed by pre-pilling of the central pile, locating the twisted jacket on this pile and then using the jacket as the piling guide for the 3 battered piles, installed using a standard pile-driving hammer aligned axially with the battered piles. Grouting or welding is then used to bond the piles to the jacket structure.

The Keystone ‘twisted jacket’ prototype foundation was successfully installed at SMartWind’s Hornsea offshore site in the UK North Sea, in October 2011, to support a met mast.



Source: GLGH Source: SmartWind website

Figure 3-45: Keystone Engineering Inc Patented Inward-battered Guide Structure Technology and Hornsea Met Mast

<u>Gifford/BMT/Freyssinet: Gravity Base Concept</u>

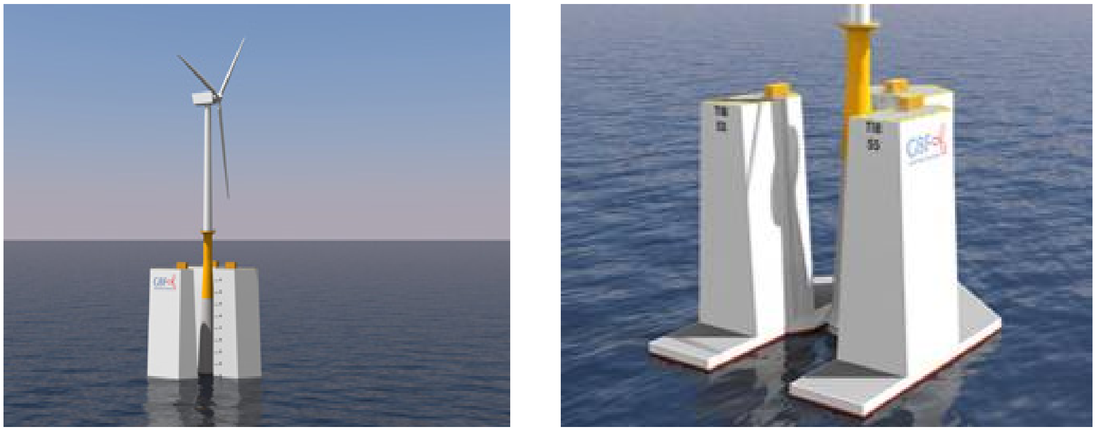
Gifford, BMT and Freyssinet formed a consortium to develop a combined foundation structure and installation technique, based on a conical, concrete GBS concept. The concept is illustrated in Figure 3-46 below. The intention of this concept is to reduce the manufacture time and cost by using slip forming and mass production techniques in fabricating the pre-stressed, concrete foundations.

In addition to streamlining the fabrication process, the consortium seeks to reduce installation costs by proposing an unmanned, semi-submersible Turbine Installation Barge (TIB). The foundation, tower, and WTG are transported and installed as a single unit by the TIB. When it reaches the site, the TIB is ballasted down to settle the foundation on the prepared seabed. The TIB then disengages, is de-ballasted and towed away for the next transport and installation cycle. The foundation, as designed, is suitable for water depths of 30-45 m.

The use of the TIB removes the need for heavy lift vessels. This tackles a major problem with CGS foundations, which is the practicality of handling large concrete structures weighing more than 2,000 tons.

However, the TIB can only transport a single foundation at a time, so a fleet may be necessary to meet tight installation schedules, particularly if weather windows are infrequent. As unmanned barges, however, fabrication is claimed to be inexpensive – approximately 1/3 of the cost of a new build jack-up vessel. The sensitivity of the proposed approach to weather conditions during either transportation or installation operations is unknown, but this would need to be carefully reviewed against the conditions anticipated at the project site.

The system has also been designed to decommission the foundations at the end of their life, by reversal of the installation procedure.



Source: GBF® Gravity Base Foundations, http://gbf.eu.com/

Figure 3-46: Gifford/BMT/Freyssinet GBS Concept

SPT Offshore & Wood Group: Tribucket Concept

SPT Offshore and Wood Group has developed a self-installing Tribucket foundation concept, with the aim that the entire foundation and turbine structure would be assembled in the construction port. The foundation is essentially a tripod space-frame structure but instead of mounting the turbine onto a central tubular member, one of the three legs consists of a vertical tubular member onto which the turbine is mounted (see Figure 3-47 below). It is claimed that the foundation is suitable for water depths of 30-60 m [18]. The complete foundation and turbine structure can be transported to the offshore wind farm site using standard marine equipment.

Transportation utilizes a flat-top deck or powered barge with the Tribucket foundation and pre-installed turbine suspended from a frame at one corner of the barge. It is proposed that the turbine will be installed on the Tribucket which is temporarily placed on the seabed adjacent to the quayside. The assembled turbine and foundation is then hoisted up by the flat-top barge and sea-fastened at one corner of the barge. The assembly is then transported to site and lowered into place, whereupon the water is pumped from the suction caisson at each of the three legs to install the structure using similar principles to those in suction bucket concept discussed above.

A benefit of the system is transporting the complete foundation and turbine structure to site and installing without the need for piling, drilling, or a vessel capable of heavy lift operations. The main drawback is that the installation vessel has to shuttle back and forth between the offshore site and construction port, carrying just one pre-assembled turbine per trip. The sensitivity to weather during transportation and installation is not known and would need careful consideration. The concept is illustrated in Figure 3-47 below.

Source: Courtesy of SPT Offshore

Figure 3-47: SPT Offshore Self-installing Wind Turbine, Tribucket Foundation Concept

3.4 Installation Vessels Review

The main types of vessels used for transportation and installation of components at offshore wind farm sites are described in “Subtopic 5.1: U.S. Ports Assessment” and discussed again in this section for completeness. It should be noted that while this section provides an overview of the primary types of vessel seen to date within the industry, numerous specialist vessels and equipment exist for particular bespoke activities involved with offshore wind development.

3.4.1 Vessel Mobilization and Costs

Most vessels require some degree of mobilizing prior to use on site. In some cases this might involve mounting a full spread of cranes and equipment onto the deck of a barge, or, at the other extreme, it may simply involve mounting a cradle onto the deck to transport a particular component. Nevertheless, this will normally lengthen the period for which the installation vessel is required and incur mobilization costs as a result.

On top of these mobilization costs, most vessel operators charge day rates, which typically form the bulk of the cost of a vessel. In some cases, fixed-cost contracts may be negotiated with contractors, effectively placing the risk of overruns on the contractor.

3.4.2 Floating Deck Barges

Deck barges are long, large, typically flat-bottom vessels with no propulsion equipment. The cheapest floating lift-craft solution for wind turbine installation purposes is formed by placing a land-based crane onto one of these deck barges. This is the most common type of vessel used to support river, coastal, and estuarine marine construction projects.

The 360º rotational capability of a crawler or mobile crane, coupled with a reasonable lift capacity of potentially greater than 100 metric tons, makes this type of vessel very versatile considering the day-rate costs. Deck barges are often used for piling and maintenance of ports and harbors. Grabs, grapples or dragline buckets can be fitted to the crane for rock-armor handling, dredging, or material handling duties and man-cradles allow inspection of marine structures.

The barge can be fitted with retractable legs, called spud-legs. When the crane is towed into position, by a tug, the legs are lowered to the seabed, and this both locates the craft in position and, if the legs are clamped to the vessel, provides some additional stability when lifting. Nevertheless, this arrangement should in no way be considered as an equivalent to the stability provided by the legs of a jack-up.

Deck barges are the most basic of craft, and any additional equipment to enhance their capability must be added to the deck of the barge during mobilization. This often includes items such as the following:

- Accommodation, storage, containerized diving-support units and office units;
- Generators, compressors, fuel bowsers, scour protection and grouting, grout-mixing equipment and grout materials;
- Mooring winches, anchors and mooring cable; and
- Cradles, racking and sea-fastening steelwork.

The limited stability of this configuration of craft means that it is unsuitable to act as the principal installation vessel for many activities. However, craft of this type will often be used for a multitude of smaller roles on any offshore construction site, and may fulfill the role of a feeder vessel, though offshore unloading will most likely be carried out by cranage on the main installation vessel in all but the most benign sea conditions.

Source: GL GH, Gunfleet Sands Wind Farm

Figure 3-48: Deck Barge with Spud-Legs, and Crawler Crane

3.4.3 Sheerleg Crane Barges

The sheerleg crane barge is fundamentally a very heavy-lift configuration of deck barge. The lifting frame fitted to the deck is permanent, and most have some form of skid-mounted or containerized propulsion unit fitted to the stern.

The lift-frame can be derricked (raised or lowered) and can often be fitted with a fly-jib, which is a boom extension affording greater outreach, or under-hook lifting height, at the expense of lift-capacity. This sort of vessel is mainly designed for heavy-lifting in sheltered waters, but the larger vessels (over 500 t) usually have some limited capability to operate offshore, in varying levels of sea-state.

Vessels of this type typically have lifting capacities of up to approximately 3,000 metric tons. They can transit laden in seas with significant wave heights of over 1 m, and carry out lifting operations in seas of between 0.5 m and 1 m significant wave heights depending on vessel size and the weight of the lifted component.

Since lifting is always over the “end” of the barge, sheerleg vessels are often a smaller beam than crane vessels of an equivalent lift capacity which can carry out fully-rotating lifts. This is a major advantage in ports with narrow lock-gates or other restrictions on beam.

Many vessel owners have manufactured their own sheerleg crane vessels, commissioning crane manufacturers and naval architects to design an arrangement for a specific purpose. A number of bespoke vessels originate from designs to meet specific project requirements, often associated with heavy bridge section lifts and, in one case, for concrete wind turbine foundations.

As an example of a Sheerleg Crane vessel, Figure 3-49 shows the ‘Taklift 4’. Its main specifications are detailed below.

Table 3-5: *Taklift 4* Sheerleg Crane Barge Specifications

Company	Vessel Name	DP [1]	Length [m]	Beam [m]	Crane Lift Capacity [metric tons]
SMIT Salvage	Taklift 4	No	83.2	36.9	2,200

1. Dynamic positioning.

Source: Alpha Ventus Website

Figure 3-49: Sheerleg Crane Vessel *Taklift 4* Working in Tandem with a Jack-up Piling Vessel

3.4.4 Semi-Submersible Heavy Lift Vessel

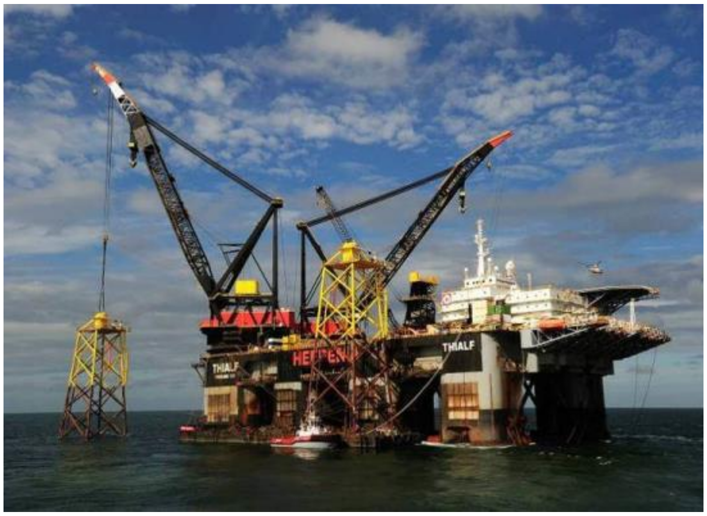
This type of vessel has been developed by the oil and gas industry to carry out placement of oil rig modules in harsh offshore conditions. The hull can be flooded, greatly increasing the deadweight of the craft and it is designed so that this ballasting operation dramatically lowers the period of roll of the craft. This change in vessel dynamics effectively "tunes-out" the majority of the wave-induced vessel motion, allowing the vessel to sit comparatively motionless in the water, largely unaffected by sea-state.

Clearly, the huge structure presents a large surface to the wind, but again, the overall stability is such that even delicate lifting operations can be carried out in deep water during relatively strong wind conditions. As an example of such vessels, Figure 3-50 shows the main specifications of the vessel *Thialf*.

Table 3-6: *Thialf* Semi-Submersible Heavy Lift Vessel Specifications

Company	Vessel Name	DP [1]	Length [m]	Beam [m]	Crane Lift Capacity [2] [metric tons]
Heerema Marine Contractors	Thialf	Yes	201.6	88.4	14,200 (at 31.2 m)

1. Dynamic positioning.
2. Crane capabilities given at a specific loading radius.



Source: Alpha Ventus Website

Figure 3-50: Semi-submersible Heavy Lift Vessel *Thialf* – Jacket Installation

The use of the semi-submersible *Thialf* at Alpha Ventus for the installation of jacket foundations as shown in Figure 3-50 was due to particular circumstances at the project. It is considered unlikely that vessels of this scale will be regularly used on offshore wind farms for turbine or foundation installation in the future. Day rates for this class of vessel are likely to be seen as prohibitive to the offshore wind installation market in general, although there could be roles for such vessels in offshore substation installation.

3.4.5 Dynamic Positioning Heavy Lift Cargo Vessels (HLCV)

Cargo vessels deliver loads rapidly and cheaply around the world and, by fitting heavy cranes to the vessel, they can collect and deliver cargo from ports without adequate crane capacity to handle the cargo. Furthermore, some of these vessels have been fitted with DP, affording them the capacity both to deliver components rapidly to offshore sites at speeds of 15-20 knots, and also to lift and position them accurately. Essentially DP is a computer-controlled system which compares real-time Global Positioning Satellite (GPS) location data with the desired position of the vessel set by the helmsman, and takes control of all vessel propulsion to pilot the vessel to the desired location and maintain it there against currents and wind drag.

Being ships, their hull-form is far sleeker than the majority of crane vessels. This may prove advantageous in development of the Northern American Great Lakes, as some vessels of this category, with 800 metric ton lift capacity, are classed as “Seawaymax”; i.e. narrow enough to pass through the locks on the St. Lawrence River and into the Great Lakes from the Atlantic.

A large number of companies operate heavy-lift cargo vessels, with the largest project cargo vessels fitted with twin 900 metric ton cranes capable of 1,800 metric ton tandem lifts. At least two of these vessels are also equipped with DP such as Jumbo Shipping’s *Jumbo Javelin* (shown in Figure 3-51) and *Jumbo Fairplayer*, although only the former has been used to date for offshore wind farm installation (placement of transition pieces in Hs <1.5 m).

Source: Jumbo Shipping website

Figure 3-51: Jumbo Shipping’s Heavy Lift Cargo Vessel *Jumbo Javelin*

The main specifications of the *Jumbo Javelin* and the *Jumbo Fairplayer* are detailed below.

Table 3-7: Jumbo Shipping DP Heavy Lift Vessels Specifications

Company	Vessel Name	DP [1]	Length [m]	Beam [m]	Crane Lift Capacity [metric tons]
Jumbo Shipping	*Jumbo Javelin*	Yes	144.2	26.7	1,800 (2 x 900 SWL)
Jumbo Shipping	*Jumbo Fairplayer*	Yes	144.8	26.8	1,800 (2 x 900 SWL)

1. Dynamic positioning.

With their high transit speeds, heavy lift capacity, and lower day rates than many equivalent lift-capacity vessels, it is considered likely that this type of vessel will see a greater role in future wind farm installation works.

Heave-compensation systems have also been retro-fitted to the cranes on these vessels, and offshore vessel-to-vessel transfers have been performed in onerous wave climates. This suggests they could also find favor as feeder-vessels as wind farms move farther offshore. Heavy lift cargo vessels have been successfully used by the oil and gas industry for a wide variety of offshore installation duties. The two-crane tandem lift configuration used by the *Jumbo Javelin,* for example, largely avoids problems with the limited under-hook height with which many single-crane vessels struggle when working with deeper water structures.

Nevertheless, these vessels lack the stability necessary to install wind turbines, so jack-ups will continue to dominate in this role.

3.4.6 Leg-Stabilized Crane Vessel

To date only two vessels of this class have entered the wind farm installation fleet and both are owned by A2SEA: *Sea Energy* and *Sea Power*. They were standard ships before they were retro-fitted with legs, and pedestal mounted Demag cc 2600 crawler crane upper-works, in a 400 metric ton lift-configuration.

This adaption has proven a versatile low-budget installation craft, which was ideal for the installation of wind turbines in the shallower sites of the early European offshore wind farms.

The stabilization legs are a hybrid between the passive spud-legs discussed in Section 3.4.2, which are clamped in position, and jack-legs, which actively jack the vessel out of the water. In the case of stabilization legs, there is some level of downward pressure exerted by the legs, which helps to react the lifted loads and improve stability in the vessel.

The origins of these vessels mean that they have good hydrodynamic hull forms and hence can transit rapidly and economically. This has allowed some sites to collect turbines from the manufacturer's load-out facility and deliver them straight to site in reasonable cycle-times, with the attendant saving the costs of a construction mobilization and storage or marshaling port. It has also won them feeder vessel duties on at least one recent project.

Source: A2Sea

Figure 3-52: Leg-stabilized Crane Vessels A2Sea *Sea Energy* (left) / *Sea Power* (right)

The main specifications of the *Sea Energy* and the *Sea Power* are detailed below.

Table 3-8: A2Sea *Sea Power* and *Sea Energy* Specifications

Company	Vessel Name	DP [1]	Length [m]	Beam [m]	Leg Length [m]	Max Water Depth [m]	Crane Lift Capacity [metric tons]
A2SEA	Sea Power	No	91.7	21.6	32	24	110[2]
A2SEA	Sea Energy	No	91.7	21.6	32	24	110[2]

1. Dynamic positioning.
2. At 20 m radius

The 24 m maximum working water depth means that the future of these crafts is potentially limited in the offshore wind installation marketplace. They may well be used for turbine, or possibly transition piece installation in shallow areas of future sites, but they are more likely to find on-going work in the O&M vessel fleet for the existing wind farms which they helped to install, and where they have the leg-length to operate.

It should be noted that these vessels are potentially suitable for installation works within the Great Lakes as they are within the Great Lakes St. Lawrence Seaway System maximum beam limit of 23.8 m.

3.4.7 Self-Propelled or Towed Jack-Up Vessels

These two distinct types of vessel have been placed under a single heading for simplicity because both fulfill similar roles and except for their means of propulsion have similar capacities. These types of vessel have been in use in the marine construction and offshore oil rig maintenance and conversion marketplaces for many years.

Early wind farms used jack-up vessels for virtually every conceivable task, largely because the sizes of the wind farms were smaller than those under construction at present and it was more economical to use one versatile vessel for all tasks, than to mobilize a number of customized vessels to carry out specific roles. At larger future sites, greater specialization of roles to site-optimized vessels can be anticipated.

The towed jack-up (or self-elevating platform, SEP) is a deck barge fitted (or retro-fitted) with jack-legs. Many are fitted with permanent cranes, but since they were designed to be customized for each new site, the existing crane can often be upgraded, within the limits of the leg-jacking capacity.

There are a number of propulsion types:

- Propelled;
- Dynamically positioned; and
- Towed.

Leg-jacking mechanisms can be:

- Hydraulic pin-jacked;
- Pneumatically gripped; or
- Rack and pinion drive.

The leg structures themselves can be:

- Tubular;
- Rectangular; or
- Lattice type.

Upgrading of leg lengths can be undertaken up to particular engineering limits, for example as defined by leg loading and tolerances at extended position, wave loading, any height limits when in the harbor or shallow waters in terms of crane operation, etc.; the appropriate leg length will be a compromise between these competing factors. Upgrading by re-craning is, however, commonly carried out – either by adding a crane to supplement the lift capacity of the crane already fitted or replacing the existing crane with a larger one (given existing deck and leg structural limitations).

The stable base provided by a jack-up is equivalent to working onshore, and onshore lift specifications can be used (except when lifting to or from floating plant). This makes these vessels ideal for installing high components such as turbine nacelles and blades and therefore jack-up vessels dominate in this critical area of work. If there are vessel shortages in the next decade, jack-up vessels will probably be restricted to turbine installation work, and attract a premium, while floating solutions will be used for the majority of other activities.

The ever increasing water-depths and foundation and turbine weights have rendered obsolete some of the vessels which carried out the first offshore wind installations, in water depths of less than 25 m and hub heights of around 70 m. Only a minority of existing vessels and a number of new-build vessels currently joining the marketplace offer sufficient capacities to install the larger 5-6 MW class turbines in waters 30-45 m deep. In the UK, there is currently a wide gap in market capability between the large areas of Round 3 sites, many of which are over 45 m deep, and the number of vessels capable of operating at those sites.

It should be noted that lattice-legged jack-ups are the vessel of choice for the oil and gas industry for water depths of over 50 m, in part due to reduced wave loading on the legs. One design appears to have a very good mix of leg length to overall size and that is the GMS Endurance – a relatively small barge, but with 65 m working capacity in benign waters, and 48 m in harsh conditions.

Jack-up vessels are capable of most roles on wind farms sites, but their stability means that they dominate the turbine installation role. Smaller vessels with longer legs are likely to find favor for the pre-piling of jacket foundations.

Source: GL GH

Figure 3-53: *Jumping Jack*, Mammoet Van Oord

3.4.8 Fall-pipe Vessels

Fall-pipe vessels are specialist, dynamically positioned vessels which feature a long, flexible pipe which passes vertically through a moon pool in the hull of the vessel. An ROV connected to the lower end of the tube allows the profile of the local seabed to be assessed and also allows the operator to “sway” the pipe and hence locate the end in a very precise fashion. The length of the pipe is adjusted according to depth by adding or removing sections as it is lowered. At the top of the pipe a conveyor system drops rocks from the holds into the pipe at a variable rate.

The dynamic positioning, flexible pipe with ROV and the variable rate conveyor systems allow fall-pipe vessels to place rock very accurately on the seabed. This functionality has multiple roles at offshore wind farm sites including:

- Seabed leveling and preparation for foundations;
- Laying scour protection; and
- Post-burial of cables.

Source: GL GH

Figure 3-54: Boskalis *Sandpiper* DP Fall-pipe Vessel

3.4.9 New Generation Wind Turbine Installation Vessels

In recent years, the market has seen the introduction of a new generation of self-propelled vessels fully customized for offshore wind turbine installation activities. Such vessels are typically equipped with jack legs, large cranes, and large deck space which allow them to work and install more and larger turbines in deeper waters than retrofitted vessels.

As an example of this new generation of installation vessels, Figure 3-55 shows the *MPI Resolution* which was one of the first vessels of this kind.

Source: GL GH

Figure 3-55: MPI *Resolution*

Even more recent is the *MPI Adventure*, capable of operation in up to 45 m water depth, which was delivered in 2011 and has recently been involved with installation works at the London Array Project in the UK. The crane on the MPI *Adventure*, is located near the aft end, but on the centerline, and is a pedestal-mounted Gusto designed GCC 1000HD, with 1,000 metric ton Safe Working Load (SWL) at 26 m radius from the crane. The crane is also capable of 160 metric tons at 73 m radius, on the auxiliary hoist, so blade lifts can be carried out across virtually the whole deck, and tower lifts over a considerable radius. Heavy loads such as nacelles are best placed on the deck close to the center of rotation of the crane, for which the aft end of the deck is ideal.

The vessel's crane has such a high lift capacity that it should be possible to jack the vessel a few meters stand-off from the edge of a quayside, and have heavier loads placed a reasonable standoff inboard of the quay-edge, and still ensure that the crane has a significant area of quayside where it can pick up turbine components within its load-radius capacity. Even so, it may be necessary to have a means of bringing heavier items to the crane, if the physical area of quayside within radius is inadequate to load the vessel. In this case, nacelles can be moved across the quayside into the crane's lift-radius using SPMTs or a skidding or rolling system.

In light of their importance in the future development of offshore wind farms, some new generation vessels available in the Northern European market have been selected and detailed in Table 3-9 below.

Table 3-9: New Generation Wind Turbine Installation Vessel Specifications

Company	Vessel Name	DP [1]	Length [m]	Beam [m]	Leg Length [m]	Max Water Depth [m]	Crane Lift Capacity [2] [metric tons]
RWE, Offshore Logistics Company	*Victoria Mathias*	Yes	100	40	78	45	1,000 (at 25 m)
Seajacks	*Zaratan*	Yes	81	41	85	55	800 (at 24 m)
Fred Olsen Windcarrier	*Brave Tern*	Yes	131	39	58	45	800 (at 24 m)
MPI Offshore	*Discovery*	Yes	138	40	72	40	1,000 (at 26 m)

1. Dynamic positioning.
2. Given at a specific loading radius.

Brave Tern[1]

Zaratan[2]

1. www.windcarrier.com/transport-and-installation-jack-up-vessels
2. http://www.4coffshore.com/windfarms/vessel-zaratan-vid539.html

Figure 3-56: New Generation Wind Turbine Installation Vessels

3.4.10

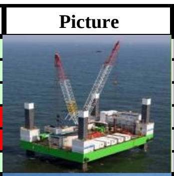
3.4.11 Vessels Previously Used for Offshore Wind Farm Installation

To date just over 30 primary installation vessels are known to have been used in foundation or turbine installation roles in the offshore wind farms across Europe and Asia. However, one wind farm developer reported using over 100 vessels at various times during construction, so it is clear that the main installation vessels are vastly outnumbered by a huge flotilla of support craft required to fulfill the myriad of tasks on site. Table 3-11 gives details of each of these vessels, and an indication of the roles for which they would be suitable. For a key to symbols, see Table 3-10.

Table 3-10: Key to Vessel Suitability

No vessel adaptation required	✓
Vessel modification or special marine operations required	~
Best practice solution	🟩
Capable in role, within water depth / weight / other limits	▨
Unsuitable	🟥 X

Table 3-11: Vessels Previously Used For OWF Installation Activities (Part 1 of 3)

Name	Suitability		Picture	DETAILS			
1. Buzzard	MPs	✓		IMO Number	10128	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	750*	Build year	1982
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	43	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	30	Max for legs depth [m]	30
	WTGs	✓		Laden draft [m]	2.97	Jacking limit, [Hs m]	~1.5m
2. Eide 5	MPs	X		IMO Number	n/a	CAPEX (estimate) [$m]	n/a
	TPs	~		Max lift [t]	1,800	Build year	1971
	PinPiles	✓		Type	Shearleg Cranebarge	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	30.5	Max speed [knots]	n/a
	Tripods	✓		Beam (Breadth) [m]	18.9	Max for legs depth [m]	n/a
	WTGs	X		Laden draft [m]	2.18	Jacking limit, [Hs m]	n/a
3. Excalibur	MPs	✓		IMO Number	n/a	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	220	Build year	n/a
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	60	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	32	Max for legs depth [m]	~40
	WTGs	✓		Laden draft [m]	2.55	Jacking limit, [Hs m]	~1.5
4. Goliath	MPs	✓		IMO Number	n/a	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	750*	Build year	2009
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	55	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	32	Max for legs depth [m]	40
	WTGs	✓		Laden draft [m]	3.6	Jacking limit, [Hs m]	1.5
5. GPS Atlas	MPs	~		IMO Number	6725212	CAPEX (estimate) [$m]	n/a
	TPs	~		Max lift [t]	400	Build year	1967
	PinPiles	✓		Type	Shearleg Cranebarge	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	46.86	Max speed [knots]	y
	Tripods	X		Beam (Breadth) [m]	20	Max for legs depth [m]	n/a
	WTGs	X		Laden draft [m]	3.28	Jacking limit, [Hs m]	n/a
6. JB114	MPs	✓		IMO Number	877072	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	300	Build year	2009
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	55.5	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	32.2	Max for legs depth [m]	40
	WTGs	✓		Laden draft [m]	3.6	Jacking limit, [Hs m]	1.5
7. JB115	MPs	✓		IMO Number	8770730	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	300	Build year	2009
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	55.5	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	32.2	Max for legs depth [m]	40
	WTGs	✓		Laden draft [m]	3.6	Jacking limit, [Hs m]	1.5
8. JB116	MPs	✓		IMO Number	n/a	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	80 (300+)	Build year	2010
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	67.5	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	40	Max for legs depth [m]	45
	WTGs	✓		Laden draft [m]	3.9	Jacking limit, [Hs m]	~1.8
9. Jumbo Javelin	MPs	~		IMO Number	9243837	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	1,800	Build year	2004
	PinPiles	✓		Type	DP2 Heavy Lift Cargo	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	144.21	Max speed [knots]	17
	Tripods	✓		Beam (Breadth) [m]	26.7	Max for legs depth [m]	n/a
	WTGs	X		Laden draft [m]	8.1	Jacking limit, [Hs m]	n/a
10. Kraken	MPs	✓		IMO Number	9522207	CAPEX (estimate) [$m]	112
	TPs	✓		Max lift [t]	300	Build year	2009
	PinPiles	✓		Type	DP Propelled Jack-up	Self-propelled [y/DP/n]	DP
	Jackets	X		Length [m]	76	Max speed [knots]	8
	Tripods	X		Beam (Breadth) [m]	36	Max for legs depth [m]	48
	WTGs	✓		Laden draft [m]	3.65	Jacking limit, [Hs m]	2
11. Leviathan	MPs	✓		IMO Number	9522219	CAPEX (estimate) [$m]	112
	TPs	✓		Max lift [t]	300	Build year	2009
	PinPiles	✓		Type	DP Propelled Jack-up	Self-propelled [y/DP/n]	DP
	Jackets	X		Length [m]	76	Max speed [knots]	8
	Tripods	X		Beam (Breadth) [m]	36	Max for legs depth [m]	48
	WTGs	✓		Laden draft [m]	3.65	Jacking limit, [Hs m]	2

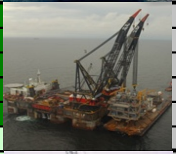
MPs: Monopiles
TPs: Transition Pieces

Table 3-11: Vessels Previously Used For OWF Installation Activities (Part 2 of 3)

12. Lisa A	MPs	✓		IMO Number	8769200	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	600	Build year	n/a
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	72.65	Max speed [knots]	n
	Tripods	X		Beam (Breadth) [m]	39.62	Max for legs depth [m]	38
	WTGs	✓		Laden draft [m]	4	Jacking limit, [Hs m]	~2
13. Matador 3	MPs	~		IMO Number	9272137	CAPEX (estimate) [$m]	n/a
	TPs	~		Max lift [t]	1500	Build year	2002
	PinPiles	✓		Type	Shearleg cranebarge	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	70	Max speed [knots]	n/a
	Tripods	✓		Beam (Breadth) [m]	32	Max for legs depth [m]	n/a
	WTGs	X		Laden draft [m]	5.8	Jacking limit, [Hs m]	n/a
14. Muhibbah JB1	MPs	✓		IMO Number	n/a	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	270	Build year	1960
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	48.79	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	30.5	Max for legs depth [m]	~30
	WTGs	✓		Laden draft [m]	3	Jacking limit, [Hs m]	~1.5
15. MPI Resolution	MPs	✓		IMO Number	9260134	CAPEX (estimate) [$m]	92
	TPs	✓		Max lift [t]	300 (600)	Build year	2003
	PinPiles	✓		Type	Jack-up crane vessel	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	130	Max speed [knots]	11
	Tripods	X		Beam (Breadth) [m]	38	Max for legs depth [m]	35+
	WTGs	✓		Laden draft [m]	4.3	Jacking limit, [Hs m]	3
16. Odin	MPs	✓		IMO Number	8768062	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	300	Build year	2004
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	46.1	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	30	Max for legs depth [m]	45
	WTGs	✓		Laden draft [m]	3.25	Jacking limit, [Hs m]	~1.8
17. Pauline	MPs	✓		IMO Number	n/a	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	200	Build year	2005
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	48	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	23.5	Max for legs depth [m]	30
	WTGs	✓		Laden draft [m]	2.5	Jacking limit, [Hs m]	~1.5
18. Rambiz	MPs	✓		IMO Number	9136199	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	3,300	Build year	1976
	PinPiles	✓		Type	Shearleg cranebarge	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	85	Max speed [knots]	~4-6
	Tripods	✓		Beam (Breadth) [m]	44	Max for legs depth [m]	n/a
	WTGs	~		Laden draft [m]	5.6	Jacking limit, [Hs m]	n/a
19. Sea Energy	MPs	✓		IMO Number	8902046	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	400	Build year	2002*
	PinPiles	✓		Type	Leg-stablised vessel	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	91.76	Max speed [knots]	8.5
	Tripods	X		Beam (Breadth) [m]	21.6	Max for legs depth [m]	24
	WTGs	✓		Laden draft [m]	4.25	Jacking limit, [Hs m]	n/a
20. Sea Jack	MPs	✓		IMO Number	8767264	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	1,300	Build year	2003
	PinPiles	✓		Type	Towed jack-up	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	91.2	Max speed [knots]	n/a
	Tripods	✓		Beam (Breadth) [m]	33	Max for legs depth [m]	30
	WTGs	✓		Laden draft [m]	3.8	Jacking limit, [Hs m]	1.5
21. Sea Power	MPs	✓		IMO Number	9002049	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	400	Build year	2002*
	PinPiles	✓		Type	Leg-stablised vessel	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	91.76	Max speed [knots]	8.5
	Tripods	X		Beam (Breadth) [m]	21.6	Max for legs depth [m]	24
	WTGs	✓		Laden draft [m]	4.25	Jacking limit, [Hs m]	n/a
22. Sea Worker	MPs	✓		IMO Number	8769705	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	400	Build year	2008
	PinPiles	✓		Type	Towed Jack-up	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	55.5	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	32.2	Max for legs depth [m]	40
	WTGs	✓		Laden draft [m]	3.6	Jacking limit, [Hs m]	1.5

MPs: Monopiles
TPs: Transition Pieces

Table 3-11: Vessels Previously Used For OWF Installation Activities (Part 3 of 3)

23. Stanislav Yudin	MPs	✓		IMO Number	8219463	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	2,500	Build year	1985
	PinPiles	✓		Type	Heavy lift vessel	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	185	Max speed [knots]	8 - 10
	Tripods	✓		Beam (Breadth) [m]	36	Max for legs depth [m]	n/a
	WTGs	~		Laden draft [m]	9 (13)	Jacking limit, [Hs m]	n/a
24. Svanen	MPs	✓		IMO Number	9007453	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	8,700	Build year	1991
	PinPiles	✓		Type	Heavy lift vessel	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	102.75	Max speed [knots]	7
	Tripods	✓		Beam (Breadth) [m]	71.8	Max for legs depth [m]	n/a
	WTGs	~		Laden draft [m]	6	Jacking limit, [Hs m]	n/a
25. Taklift 4	MPs	~		IMO Number	8010506	CAPEX (estimate) [$m]	n/a
	TPs	~		Max lift [t]	2,400	Build year	1981
	PinPiles	✓		Type	Shearleg crane	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	83.2	Max speed [knots]	~6
	Tripods	✓		Beam (Breadth) [m]	36.9	Max for legs depth [m]	n/a
	WTGs	X		Laden draft [m]	6.02	Jacking limit, [Hs m]	n/a
26. Taklift 7	MPs	~		IMO Number	7829273	CAPEX (estimate) [$m]	n/a
	TPs	~		Max lift [t]	1,600	Build year	1976
	PinPiles	✓		Type	Shearleg crane	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	72.56	Max speed [knots]	~6
	Tripods	✓		Beam (Breadth) [m]	30.5	Max for legs depth [m]	n/a
	WTGs	X		Laden draft [m]	4.9	Jacking limit, [Hs m]	n/a
27. Thor	MPs	✓		IMO Number	9577147	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	500	Build year	2010
	PinPiles	✓		Type	Towed Jack-up	Self-propelled [y/DP/n]	n
	Jackets	✓		Length [m]	70	Max speed [knots]	n/a
	Tripods	X		Beam (Breadth) [m]	40	Max for legs depth [m]	50
	WTGs	✓		Laden draft [m]	3.5(7.4)	Jacking limit, [Hs m]	~2
28. Titan 2	MPs	X		IMO Number	9495753	CAPEX (estimate) [$m]	60
	TPs	✓		Max lift [t]	400	Build year	2008
	PinPiles	✓		Type	Self propel'd jackup	Self-propelled [y/DP/n]	n
	Jackets	X		Length [m]	51.97	Max speed [knots]	4.3
	Tripods	X		Beam (Breadth) [m]	36.68	Max for legs depth [m]	60.96
	WTGs	✓		Laden draft [m]	4.27	Jacking limit, [Hs m]	1.5
29. Thialf	MPs	✓		IMO Number	8757740	CAPEX (estimate) [$m]	$1Bn
	TPs	✓		Max lift [t]	14,200	Build year	1985
	PinPiles	✓		Type	Semi-sub HLV	Self-propelled [y/DP/n]	DP
	Jackets	✓		Length [m]	201.6	Max speed [knots]	7
	Tripods	✓		Beam (Breadth) [m]	88.4	Max for legs depth [m]	n/a
	WTGs	~		Laden draft [m]	11.8 - 31.6	Jacking limit, [Hs m]	n/a
30. Wind	MPs	✓		IMO Number	9107851	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	200	Build year	1995
	PinPiles	✓		Type	DP2 jackup	Self-propelled [y/DP/n]	y
	Jackets	X		Length [m]	55	Max speed [knots]	~ 6
	Tripods	X		Beam (Breadth) [m]	18	Max for legs depth [m]	30
	WTGs	✓		Laden draft [m]	2.4	Jacking limit, [Hs m]	~1.5
31. Wind Lift 1	MPs	✓		IMO Number	9516686	CAPEX (estimate) [$m]	(110)
	TPs	✓		Max lift [t]	500	Build year	2010
	PinPiles	✓		Type	DP2 Jack-up vessel	Self-propelled [y/DP/n]	DP
	Jackets	✓		Length [m]	93	Max speed [knots]	6 - 8
	Tripods	X		Beam (Breadth) [m]	36	Max for legs depth [m]	45
	WTGs	✓		Laden draft [m]	3.5	Jacking limit, [Hs m]	1.8
32. Fen Jin	MPs	✓		IMO Number	9516686	CAPEX (estimate) [$m]	n/a
	TPs	✓		Max lift [t]	500	Build year	2006
	PinPiles	✓		Type	Shearleg crane	Self-propelled [y/DP/n]	y
	Jackets	✓		Length [m]	100	Max speed [knots]	n/a
	Tripods	✓		Beam (Breadth) [m]	41	Max for legs depth [m]	n/a
	WTGs	✓		Laden draft [m]	4.8	Jacking limit, [Hs m]	n/a

MPs: Monopiles
TPs: Transition Pieces

3.4.12 Summary of Suitability of Vessels for Offshore Wind Farm Installation Activities

Table 3-12 categorizes the activities on sites with monopile, space frame foundations, and GBS foundations in various water depths, and lists the suitability of each class of vessel as described above.

Table 3-12: Suitability of Vessel Types for Offshore Wind Farm Installation Activities

Activity	Water Depth [m]	Floating Deck Barge with Crane	Sheer-leg Crane Barge	Semi-submersible / heavy Lift Vessel	DP Heavy Lift Cargo Vessels	Heavy Lift Cargo Vessels	Leg-stabilized Crane Vessel	Self-Propelled and Towed Jack-up Craft
Monopile driving	< 10	~	~	✓	~	~	✓	✓ □
	10 – 20	~	~	✓	~	~	~	✓ □
	20 - 30	X	~	✓	~	~	~	✓ □
	> 30	X	~	✓	~	~	X	✓ □
Jacket / Tripod pre-piling	30 - 40	~	~	✓	✓	~	✓	✓ □
	40 - 50	~	~	✓	✓	~	✓	✓ □
	50 - 60	~	~	✓	✓	~	✓	✓ □
Jacket installation	30 - 40	~	✓	✓	✓	~	X	✓ □
	40 - 50	X	✓	✓	✓	~	X	✓ □
	50 - 60	X	✓	✓	✓	~	X	✓ □
Tripod installation	10 - 20	~	~	✓	✓	✓	X	~ □
	20 - 30	~	~	✓	✓	✓	X	~ □
	30 - 40	X	~	✓	~	~	X	~ □
	40 - 50	X	~	✓	~	~	X	~ □
	50 - 60	X	~	✓	X	X	X	~ □
GBS Structures	10 - 20	~	✓	✓	~	~	X	X
	20 – 30	X	✓	✓	X	X	X	X
	30 - 40	X	~	✓	X	X	X	X
Transition piece installation	10 - 20	~	✓	✓	✓	✓	✓	✓ □
	20 - 30	~	✓	✓	✓	✓	~	✓ □
	30 - 40	X	✓	✓	✓	✓	X	✓ □
	40 - 50	X	✓	✓	✓	✓	X	✓ □
	50 - 60	X	✓	✓	✓	✓	X	✓ □
Turbine installation 3 MW	10 - 20	X	X	X	X	X	✓	✓ □
	20 - 30	X	X	X	X	X	~	✓ □
	30 - 40	X	X	X	X	X	X	✓ □
	40 - 50	X	X	X	X	X	X	✓ □
	50 - 60	X	X	X	X	X	X	✓ □

Activity	Water Depth [m]	Floating Deck Barge with Crane	Sheer-leg Crane Barge	Semi-submersible / heavy Lift Vessel	DP Heavy Lift Cargo Vessels	Heavy Lift Cargo Vessels	Leg-stabilized Crane Vessel	Self-Propelled and Towed Jack-up Craft
Turbine installation 5 MW		X	X	X	X	X	X	✓ □
Turbine installation >5 MW		X	X	X	X	X	X	✓ □
Substation topside		X	✓	✓	✓	~	X	X

1. Key to Vessel Class Suitability:
   - ✓: No vessel adaptation required
   - ~: Vessel modification or special marine operations required
   - X: Unsuitable
   - □: Depending on water depth limits

   Substation Jackets as per heavy weight WTG jackets

3.5 Potential United States installation Vessels

There is significant restriction in place on the vessels that are able to operate in U.S. waters, due to the Merchant Marine Act of 1920 (commonly known as the Jones Act). The Jones Act is a United States federal statute that regulates maritime commerce in U.S. waters and between U.S. ports. It requires that all goods transported by water between U.S. ports be carried by U.S.-flag ships. However, according to [19], the Jones Act does not prevent the use of non-U.S. flagged vessel for static installation purposes, such as pile driving or erection of a wind turbine, provided the vessel does not move off station with merchandise (e.g. foundations or turbine components, etc.) on board.

Added to the vessel constraints imposed by the Jones Act is the limitation for potential installation vessels when considering a deployment of offshore wind farms within the Great Lakes. Access to the lakes via the St Lawrence Seaway is a major constraint for installation vessels.

For the reasons mentioned above, Douglas-Westwood has identified potential vessels which are Jones Act-compliant and which could be used for the installation of future U.S. offshore wind energy projects [20]. A description of some of these vessels as well as some vessels identified by GL GH and their potential role within the deployment of offshore wind farms within the U.S. is provided below.

3.5.1 U.S. Floating Deck Barges

Because of the developed and active marine operations in the U.S., there are many deck barge suppliers and operators available in the local market. These vessels could be used as feeder vessels or for some of the wind farm installation activities if equipped with appropriate lifting cranes. As indicated by Douglas-Westwood, one of the Jones Act-compliant vessels is the *Niagara Spirit* operated by McKeil Marine. This barge operates in the Great Lakes region and its specifications are shown in Table 3-13 below.

Table 3-13: *Niagara Spirit* Barge Specifications

Company	Vessel Name	DP[1]	Length [m]	Beam [m]	Cargo Capacity [metric tons]
McKeil Marine	Niagara Spirit	No	99	23	7,800

1. Dynamic Positioning

Source: McKeil Marine

Figure 3-57: Deck Barge *Niagara Spirit* by McKeil Marine

An example of a U.S. deck barge supplier identified by GL GH is McDonough Marine Service. McDonough provides a wide range of inland and ocean barges within the southern United States. The specifications of its *Marmac 300* deck barge are presented in Table 3-14 below.

Table 3-14: U.S. Deck Barge *Marmac 300* Specifications

Company	Vessel Name	DP[1]	Length [m]	Beam [m]	Cargo Capacity [2] [metric tons]
McDonough Marine Service	Marmac 300	No	91	30	10,000

1. Dynamic Positioning
2. Cargo capacity defined at load line.

Source: http://www.mcdonoughmarine.com

Figure 3-58: Deck Barge *Marmac 300* by Mcdonough Marine Service

3.5.2 U.S. Sheerleg Crane Vessels

GL GH identified one Sheerleg Crane Vessel with U.S. flag, the Donjon Marine Co. *Chesapeake 1000*. The *Chesapeake 1000* characteristics are shown in Table 3-15.

Table 3-15: U.S. *Chesapeake 1000* Sheerleg Crane Vessel Specifications

Company	Vessel Name	DP1	Length [m]	Beam	Crane Lift
Donjon Marine	Chesapeake	N	58	30.7	907 (at 19 m)

1. Dynamic Positioning
2. Crane capabilities given at a specific loading radius.

3.5.3 U.S. Semi-submersible Heavy Lift Vessels

Some of the Semi-Submersible vessels identified by Douglas-Westwood which are Jones Act-compliant are detailed below. These vessels could be used to transport wind farm components from the manufacturing port to a marshaling port. Advantages of using a marshaling port are discussed in Section 3.2.4.

Table 3-16: Semi-Submersible Heavy Lift Vessels in U.S.

Name of Ship	Ship Type	Length [m]	Breadth [m]	Deadweight [metric tons]	Propulsion Type
Montford Point	Heavy Load Carrier, semi-submersible	239.3	49.9	60,000	Oil Engine(s)
Nassco 541 (ex-2013)	Heavy Load Carrier, semi-submersible	239.3	49.9	60,000	Oil Engine(s)
John Glenn	Heavy Load Carrier, semi-submersible	239.3	49.9	60,000	Oil Engine(s)
Nassco 542 (ex-2014)	Heavy Load Carrier, semi-submersible	239.3	49.9	60,000	Oil Engine(s)

It should be noted that all of these vessels have been ordered by the U.S. Navy and some of them are still under design and construction. The consideration of such vessels for a future U.S. offshore wind energy industry would require the ordering of new vessels, the costs of which could be prohibitive. Furthermore, the current design of these future vessels lacks heavy lift equipment capable of performing installation activities, so additional cranage would need to be added to fulfill such roles.

3.5.4 U.S. DP Heavy Lift Cargo Vessels

DP Heavy Lift Cargo Vessels (HLCV) vary both in cargo capacity and lift capacity, each of which affects the ability to transport components. In particular for offshore wind, lift capacity can become a limitation for larger turbine sizes, foundations and nacelles. Douglas-Westwood has identified some heavy lift cargo vessels equipped with DP, one of which is the McDermott *Derrick Barge 16* detailed in Table 3-17.

Table 3-17: DP Heavy *Derrick Barge 16* Specifications

Company	Name of Ship	DP[1]	Length [m]	Beam [m]	Crane Lift Capacity [2] [metric tons]
McDermott	Derrick Barge 16	Yes	121.9	30.5	635 (at 19 m)

1. Dynamic Positioning
2. Crane capabilities given at a specific loading radius.

As previously mentioned, with their high transit speeds, heavy lift capacity and lower day rates than other equivalent lift-capacity vessels, it is likely that this type of vessel will see a greater role in future wind farms in the U.S. However, the use of jack-up vessels for the installation of the wind turbines would still be required.

3.5.5 U.S. Jack-Up Vessels

GL GH has identified jack-up vessels which could potentially be used for the installation of foundations and wind turbines within the U.S.; these are presented in Table 3-18.

Table 3-18: Jack-Up Vessels for Installation of U.S. Offshore Wind Farms

Company	Vessel Name	Length [m]	Beam [m]	Legs Length [m]	Max Water Depth [m]	Crane Lift Capacity [1] [metric tons]
Montco Offshore Inc	*L/B Robert*	55.5	41.1	102.1	85	500 (at 10 m)
KS Energy Service Limited (Atlantic Oilfield Services)	*Titan 2*	89.9	74.7	85.3	61	2 x 200 (at 9 m)
Superior Energy Services	*Superior Influence / Superior Respect*	81.1	33.5	80.8	61	181 (at 8 m)
Hercules Liftboats	*Man O War*	40.7	24.1	69.8	55	100 (at 9 m)
Hapo International Barges BV	*Lisa A*	72.6	39.6	52.3	33	600 (at 12.2 m)
Weeks Marine	*R. D. MacDonald*	79.2	23.8	unknown	30	750 (unknown)

1. Crane capabilities given at a specific loading radius.

These jack-ups are capable of most roles on wind farms sites, but their stability means that they are more suitable for the turbine installation role. Small jack-ups with long legs are likely to find favor for the pre-piling of jacket foundations while large jack-ups would be more suitable to transport and install the wind turbine main components.

It should be noted that the new-build *R.D. MacDonald* is designed to be able to access the Great Lakes through the St. Lawrence Seaway and hence represents the largest jack-up vessel known to be able to operate in both U.S. coastal waters and the Great Lakes.

1. www.montcooffshore.com/Robert

Figure 3-59: *L/B Robert* (Jones Act-compliant)

3.5.6 U.S. Cable Laying Vessels

Douglas-Westwood has identified two Jones Act-compliant Cable Laying vessels, as described in Table 3-19 [20].

Table 3-19: Jones Act-compliant Cable Laying Vessels Identified by Douglas-Westwood

Company	Vessel Name	Length [m]	Beam [m]
Anseeuw A	LCT-889 (ex-1987)	31.7	9.7
Transport & Tankers Corp	Sidney Solar (ex-1994)	47.2	11.6

3.5.7 Great Lakes Installation Vessels' Access Constraint

After reviewing the potential installation vessels that could be deployed or utilized in the future development of offshore wind farms within the U.S., it is important to comment on the main constraint that the access to the Great Lakes region will represent for most of these vessels.

If considering the installation of offshore wind farms within the Great Lakes, if not locally sourced, most of these installation vessels would have to access the Lakes from the Atlantic Ocean by crossing the Great Lakes Saint Lawrence Seaway System. The vessels that can cross the Seaway system are limited by the size of the locks that form the Seaway. The maximum allowed vessel size for the system is: 225.6 m long, 23.8 m wide or beam, and 8.1 m deep. This maximum permissible vessel size is informally known as the Seawaymax and is of vital importance when considering the vessels that could be used for the installation of wind turbines and the balance of plant of an offshore wind farm within the Lakes.

If considering these limits, it is easy to observe that the width of the Seaway is the main access constraint for most of the described installation vessels and that only the cable laying vessels mentioned above and the *Niagara Spirit* Deck Barge which already operates within the Great Lakes are capable of crossing the Seaway. Therefore, installation vessels would have to be specifically sourced from within the Great Lakes Region or be designed and built considering these limitations. Furthermore, if considering chartering already-built vessels for the installation of a wind farm in the Lakes, the options are very limited, as presented in Table 3-20.

Table 3-20: Installation Vessels Able to Navigate the Great Lakes St. Lawrence Seaway System

No.	Company	Name of Vessel	Type	Beam [m]
1.	A2SEA	*SeaEnergy*	Leg-Stabilized Vessel	21.6
2.	A2SEA	*SeaPower*	Leg-Stabilized Vessel	21.6
3.	Besix	*Pauline*	Jack-up Vessel	23.5
4.	DBB Jack-Up	*Wind*	Jack-up Vessel	18.0
5.	Eide Marine Services A/S	*Eide 5*	Sheerleg Crane Vessel	18.9
6.	GPS Marine Contractors Ltd	*GPS Atlas*	Sheerleg Crane Vessel	20.0
7.	Boskalis	*Sandpiper*	Fall-pipe Vessel	22.9

4 O&M METHODOLOGY AND VESSELS REVIEW

The review provided in this Report aims to describe the alternative approaches to the operation and maintenance of offshore wind projects. This section comprises publically available information from manufacturers' websites and promotional material, as well as appropriate conference papers and GL GH experience. In addition, GL GH has contacted some suppliers to obtain up-to-date information on the status of the access solutions, and their limitations with respect to their potential implementation within the U.S.

For these Operation and Maintenance activities, GL GH has reviewed and detailed the typical technical requirements from current and emerging industry experience and practices. The study details the potential requirements of an emerging U.S. offshore wind industry, taking into consideration anticipated future trends in offshore wind technology e.g. wind turbine size, transfer vessel capabilities, access systems, etc.

This review has been used to inform the O&M modeling and analysis work described in Section 7, through the identification of the likely emerging and future approaches and trends within the Offshore Wind O&M Sector.

4.1 Operation and Maintenance Requirements of an Offshore Wind Farm

As the name suggests, the operation and maintenance activities of an offshore wind farm can be divided into two main tasks:

- Monitoring, controlling and coordinating the wind farm operations; and
- Maintenance activities, which are typically sub-categorized into scheduled and unscheduled maintenance of the turbines and the balance of plant (BoP).

Nowadays, developments in advanced control and monitoring systems enable operators to undertake routing checks of operational data and to control the turbines from a remote onshore location, while scheduled and unscheduled maintenance works require the transportation and transfer of technicians to the offshore structures. These maintenance activities, particularly the access logistics associated with them, are one of the most significant operational challenges facing the offshore wind energy market and therefore are the main subject of this review.

4.1.1 Scheduled Maintenance / Inspection

This maintenance category comprises any task which is pre-planned at the design stage and normally requires the turbine to be temporarily stopped for maintenance work to be undertaken. Offshore scheduled maintenance intervals of 1 year are emerging as the normal practice in contrast to the quarterly or bi-annual approach typically witnessed onshore. This reflects the greater expense, risk and effort associated with offshore access.

The turbine manufacturer should be contractually required to supply a complete list of scheduled maintenance tasks. These tasks can be performed by trained technicians who are transported to the turbines via marine vessels or helicopters and who then perform the maintenance services equipped with basic tools and consumables.

Such scheduled works are often conducted on a seasonal basis, with the bulk of work being carried out in the summer to maximize the probability of access and minimize lost production. This approach may lead to the need for additional resources (vessels, equipment, and technicians) to be brought in during these campaigns.

4.1.2 Unscheduled Maintenance

Any unplanned maintenance activities resulting from a failure of a system, sub-system, or component fall within this group. The level of corrective action, and the impact of the unscheduled maintenance upon the wind farm availability, depends on the severity of the failure. Most failures occur within the wind turbine generator systems and only affect the output of individual turbines, while failure events within the substations or cables occur far less frequently but can have a greater impact on the number of turbines affected depending upon their location.

4.2 Access Methodologies

Current and planned offshore wind farms around the world are maintained by a variety of different operational strategies and access methodologies. Such access strategies are predominantly concerned with the transportation of technicians, parts and equipment from operations and maintenance base and their subsequent safe transfer between the vessel and the offshore structures.

In the early days of offshore wind development in Europe, much of the industry was still of the “onshore” mindset and consequently some of the issues associated with a marine environment were not considered in sufficient detail. Access to the offshore structures, during both construction and subsequently during the operational phases, were two such areas where practices fell short of optimum requirements, resulting in delays and poor initial performance across many early projects.

For marine access, sea-state during transfer onto the structures is usually the primary determining factor, typically quantified in terms of significant wave height (Hs) in units of meters. Other potential limitations include current, wind speed, sea ice, visibility and water depth. These restrictions result in the occurrence of “weather windows” during which all these factors are within the limitations of a particular vessel or access solution. As a result of the limited weather windows in which access may be achieved, even small unscheduled failures or diagnosis visits can lead to the accruement of considerable downtime and lost production, particularly as periods of onerous weather and limited access are likely to coincide with periods of high wind and therefore high potential for energy generation.

To date, most projects utilize onshore bases and typically use work boats to transport technicians from port to the site where they transfer onto the offshore structures using a simple “step over” approach, as outlined in Section 4.2.2.

In more advanced strategies, the uses of advanced vessels or helicopters are emerging for some existing and planned projects. Furthermore, as projects begin to be based further offshore, work boats may also operate from fixed offshore bases, ‘floatels’ or motherships to substantially reduce the time required for transiting to and from site. Such offshore-based approaches require technicians to live for some or all of the year on offshore accommodation near the vicinity of the wind farm, whether fixed or floating, in a similar manner to the approach adopted in offshore oil and gas.

For the purposes of this review, access strategies have been classified under three main categories:

- Onshore-based marine access (e.g. work boats, SWATH vessels, helicopters etc., based at a coastal port);
- Helicopter access; and
- Offshore-based marine access (e.g. offshore accommodation platforms, floatels etc., where technicians live offshore).

These approaches to O&M working practice will be assessed in further detail in Sections 4.2.3, 4.2.4, 4.2.5, respectively, with a description of the current practices within operational offshore wind farms as well as some future trends in emerging technology and approach which might be implemented as the U.S. offshore wind industry matures.

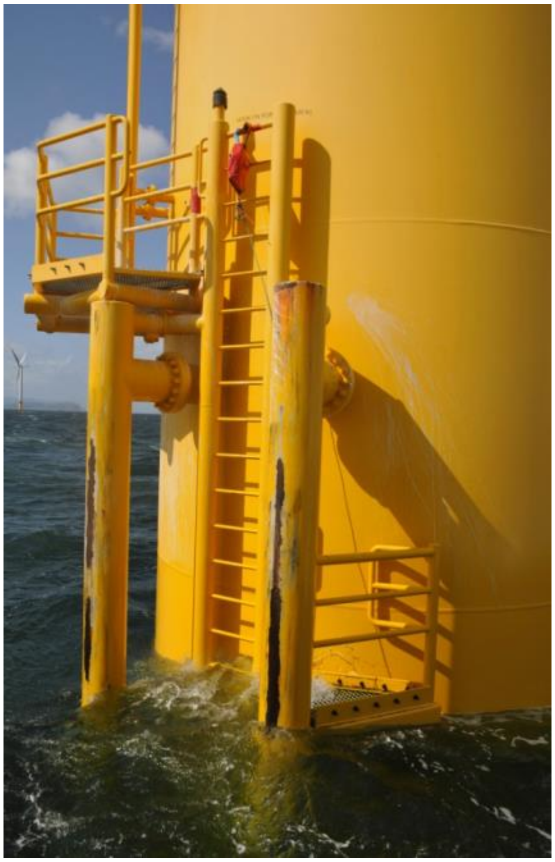
4.2.1 Boat Landing and Small Cranage

Clearly, a fundamental parameter of any offshore access strategy is the design and configuration of the secondary steelwork on the foundation or transition piece with which the vessel docks. The majority of turbines installed to date use monopile foundations; however, GBS, jackets, tripods and tri-piles are also used as conditions, water depths, turbine sizes, and soil conditions dictate.

All of these foundation types constructed to date have at least one boat landing on at least one leg. The basic premise of a boat landing is to provide two vertical tubular spars against which the vessel fender can push at any state of tide and form a friction grip. Between these tubular spars, and somewhat set back, is a ladder, onto which technicians may step from the front of the vessel. Figure 4-1 and Figure 4-2 show examples of these arrangements at low tide and high tide, respectively.

Source: GL GH

Figure 4-1: Boat Landing at Low Tide



Source: GL GH

Figure 4-2: Boat Landing and Intermediate Platform at High Tide

The boat landing will typically be oriented to provide the greatest likelihood of suitable weather conditions for a safe transfer. Normally this will result in the vessel bow or stern facing into the predominant wave and current directions, such that waves or strong current across the vessel are less likely. However, at some projects more than one boat landing per foundation is adopted in order to provide a better coverage of directions from which a vessel can dock, thereby providing more weather windows in which access can be secured.

At the top of the foundation it is normal to have a platform which runs around the circumference of the tower base, from which the door into the tower may be reached and a davit crane may be deployed to lift or lower parts and tools from the vessel below. A typical platform arrangement is shown in Figure 4-3.

Such davit cranes are the principal method for lifting objects onto and off the vessel and the weight limit of such lifts will depend upon both the safe working load of the davit and the current sea conditions. Typically, davit cranes are limited to somewhere between 100 – 2,500 kg depending upon the specifications of the particular crane adopted, but the true loading will depend on dynamic factors such as snatch loading induced by the current sea state.

Larger items that are required in the nacelle may be hoisted directly from the vessel or the tower base platform using a second davit or knuckle-boom crane located in the nacelle. This will typically be capable of lifting loads of up to 500 – 5,000 kg depending on the turbine and nacelle configuration.

Source: GL GH

Figure 4-3: Platform and Davit at Top of Foundation / Base of Tower

Some large vessels with dynamic positioning capabilities, such as “floatels” or “motherships” (see Section 4.2.4) may use specialist gangways to dock directly with the platform at the base of the tower via a gate in the railings, but to date the majority of access has been accomplished via the standard boat landing using the “Step-Over” approach.

4.2.2 “Step-Over” Approach

Currently, most offshore wind farms in the UK and continental Europe are accessed via traditional work boats, with technicians stepping across from the bow of the vessel directly to the turbine access ladder. An outline of this standard approach to offshore access is as follows:

- Weather forecasts and measured site data are analyzed and if conditions are acceptable, a work boat with its crew is prepared for departure from the O&M base port.
- Once the vessel has arrived at the wind turbine requiring maintenance, the captain of the vessel assesses the conditions and decides if he/she considers it safe to transfer. At some sites, two alternative boat landings are fitted to the turbine foundation to allow the captain to select the most appropriate given wind, wave, and current directions.
- The vessel pulls up to the boat landing at a relatively slow speed (<1 knot at final approach). The vessel bow fenders will be purposely designed to fit with the turbine landing system. At this moment, the captain is able to adequately guide the vessel into position.
- When the vessel is in position the vessel thrusters are used to push the vessel directly against the turbine landing system, whereby the bow of the vessel is held in position by the frictional force exerted by the vessel. The captain will typically aim to make this frictional grip when the bow of the vessel is high in the water due to the crest of a wave. This should prevent the buoyancy of the vessel from causing the fender to slip on the boat landing and hence restrict the movement of the vessel for a period of time.

Source: GL GH

Figure 4-4: Boat Landing on a Monopile Foundation

Source: GL GH

Figure 4-5: Work Boat Interfacing with a Boat Landing

- The technicians who are accessing the turbine make their way to the bow of the vessel where the vessel mate will be monitoring the transfer. The technicians are able to hold on to support railings until they and the mate are confident of a safe transfer. A transfer will only be made if the captain and the technicians themselves are comfortable in doing so. Only one technician is in a position to step across at any given time. The captain meanwhile remains vigilant for oncoming large or freak waves.

- When the conditions are right, the first technician lets go of the vessel support rails, steps across to the turbine ladder and grabs the ladder in one movement. The technician then scales the ladder to the first rest platform. Depending upon the specific operating procedures at the site and the height of the first platform above the present tidal height, a fall arrest system may be used for this initial climb.
- To minimize the chances of vessel slippage during marginal weather, the vessel may then pull away 10 m and "land" at the turbine a second time if the helmsman believes it necessary. The second technician then steps across, following the same procedure.

At any time that turbine access is being undertaken and only one vessel is within the vicinity, it must be equipped for dealing with man overboard incidents.

If an experienced vessel operator is contracted, then it will employ its own working practices and procedures, which must conform to those of the project operator and project owner. Most service vessels currently in operation are aluminum or glass-fiber catamarans with a length of approximately 12 – 25 m, as further discussed in Section 4.2.3.

4.2.3 Onshore-based Marine Access

A wide range of conventional and specialist vessels are currently available to provide frequent personnel transportation and access to offshore wind farm developments from an onshore location. These vessels vary in capacity, speed, and significant wave height (Hs) transferring capabilities and include:

- Quick response vessels (e.g. Rigid Inflatable Boats (RIB));
- Work boats (traditional catamarans);
- Small Water-plane Area Twin Hull vessels (SWATH vessels); and
- Hovercrafts or amphibious vehicles (for ice or inter-tidal conditions).

A review of these vessels is provided in the following sub-sections.

Quick Response Vessels

There are a range of Rigid Inflatable Boats (RIBs) and other lightweight vessels currently available for offshore wind farm operations. These vessels are small and designed for light work and as quick response during installation and operation activities offshore. The vessels are typically in the range of 5 to 15 m length and capable of transferring up to 12 technicians and of achieving speeds of approximately 35 knots, well in excess of those attained by most aluminum catamarans and larger work boats. Quick response vessels will typically dock with turbines and other structures in a similar manner to that utilized for work boats (see Section 4.2); however, given the generally narrower bow of such vessels, they may employ a different fender design for docking with the boat landing, such as the approach shown in Figure 4-6, wherein the vessel docks with just one of the two vertical tubular spars of the boat landing.

Source: GL GH

Figure 4-6: Example of Fender Design on a RIB Quick Response Vessel

Although these vessels offer greatly reduced transit times, they are unsuitable for personnel transport over large distances and/or in onerous conditions. They may, however, offer advantages over work boats for some operations, such as when quick fault diagnosis and subsequent turbine restart is possible without the need for substantial spare parts or additional equipment, for use as supplementary transfer vessels when a greater number of service crews are present for a particular maintenance campaign, and for in-field transfers, particularly in sheltered sites in the summer months when conditions are relatively benign. Such vessels may also be utilized as “daughter crafts” in conjunction with floating offshore-based operations (see Section 4.2.4).

Indicatively, quick response vessels might be capable of transferring technicians onto offshore structures in 0.75 m – 1.5 m Hs, depending on their size and hull design as well as the profile, frequency, and direction of the waves.

Figure 4-7 and Figure 4-8 show an example of these vessels.

Source: GL GH

Figure 4-7: Quick Access Vessel

Figure 4-8: WindSpeed Quick Access Vessel by Windcat.

Workboats

Work boats form an integral part of O&M strategies for currently operational projects and are typically larger and more comfortable than the Quick Response Vessels. Their purpose is generally to transfer personnel and moderate-sized parts to near-shore projects in support of both scheduled and unscheduled maintenance activities. In some cases, work boats may also operate from fixed offshore bases, floatels or motherships as discussed in Section 4.2.4.

Work boats are typically designed with large foredecks to allow plenty of space and flexibility for transporting components and equipment. This arrangement also means that all items are located underneath the turbine davit or nacelle crane when the vessel is in position against the boat landing (see Section 4.2.1). The maximum size of parts, tools and consumables that may be transported is usually governed more by the lifting capacity of the davit or nacelle crane on the turbines than by the deck capacity of the work boat.

Industry-quoted figures suggest that work boats may typically be used to transfer technicians to offshore structures in up to ~1.5 m Hs; however, operating experience suggests that this is often not achievable, especially for smaller vessels.

To better illustrate some of the work boat designs currently available, GL GH has included a selection of some UK and European operators below. It should be noted, however, that there is an extensive range of such providers and operators with many more emerging in response to the high demand for these vessels. Therefore, those operators outlined below are included only for indicative purposes of the general arrangement and specifications of work boats.

<u>Windcat Work Boats</u>

Morelli and Melvin Design & Engineering Inc. manufactures the Windcat, an aluminum-hulled workboat suitable for transferring up to 12 personnel to the site and onto the turbine.

There are currently four variants of Windcat vessels that have been procured, and are operated by Windcat Workboats (WCW), the basic specifications of which are included in Table 4-1.

Table 4-1: Windcat Variants

Variant	*MK I*	*MK II*	*MK III*	*MK IV*
Length Overall [m]	15	16	18	27
Beam [m]	6.1	6.1	6.1	9.0
Draft [m]	1.9	1.9	1.9	1.7
Classification	MCA 2	MCA 2	MCA 2	DNV + 1A1 HSLC
Max Speed [knots]	25	28	28	31
Cruising Speed [knots]	21	25	25	26
Propulsion	Propellers / Jets	Propellers	Propellers	Propellers
Accommodation	Seating for 12, shower, toilet, cooking	Seating for 12, shower, toilet, cooking	Seating for 12, shower, toilet, cooking, TV, computer facilities	Seating for 45, toilet, TV, computer facilities
Deck Crane	2 ton SWL	2 ton SWL	2 ton SWL	2 ton SWL

The natural evolution of offshore wind farm support vessels is moving designs towards larger vessels such as the *MK IV* variant, with improved crew comfort, better sea-keeping characteristics and more storage space, to provide a better access solution for wind farms located farther offshore in more onerous climates. In addition, Windcat appears to have settled on a propulsion system, as although several of the *MK I* vessels are powered by waterjets, the most recently manufactured Windcat vessels are powered by propellers. Figure 4-9 and Figure 4-10 show some of the Windcat vessels in operation.

Source: Windcat

Figure 4-9: Windcat *MK I* during Personnel Turbine Access Position

Source: Windcat

Figure 4-10: Windcat *MK IV* during Transit

Currently, WCW supplies Windcats for use in the O&M of Arklow Bank, Thornton Bank, and Robin Rigg wind farms. The vessels were also previously used in the O&M phase at Egmond aan Zee, and are currently being used to support construction activities for several UK and Northern European projects.

The manufacturers claim that operational experience from Arklow Bank has demonstrated that the Windcat is able to safely transfer crews to the turbine in seas of up to 2 m significant wave height (Hs). However, GL GH considers that this is not within the normal operating envelope of the vessels. More information on Windcat vessels can be found in [21].

North Sea Logistics

Another operator of workboats is North Sea Logistics (NSL). Based in Blyth, in the UK, NSL is currently contracted by turbine Original Equipment Manufacturer (OEM) Vestas to supply vessel cover for some of the said OEM's UK offshore wind farms. NSL's vessels are constructed by Alnmaritec, based in the UK, who has experience in delivering work boats to the offshore oil and gas industry. NSL supplied a range of work boats which are currently used in the operation and maintenance of several UK offshore wind projects.

The *Celtic Wind, Celtic Challenger, Celtic Warrior* and *Celtic Storm* are employed at North Hoyle, Barrow, Scroby Sands, and Kentish Flats, respectively, and are all derivatives of the *Wave-Train 1300*, an aluminum alloy catamaran propelled by two water jets, achieving cruising speeds of approximately 18 knots. Minor modifications to the *Wave-Train 1300* design have been made following early operational experience, and the *Celtic Challenger* is fitted with a hydraulic deck crane for cargo handling. Figure 4-11 and Figure 4-12, respectively, show the *Celtic Warrior* and *Celtic Challenger* in action.

Figure 4-11: NSL's *Celtic Warrior*

Turbines are accessed from the vessels in a similar manner to that of other work boats, by steering the vessel against the boat landing and applying the throttle to create enough friction to hold the vessel steady. This method facilitates safe transfer for significant wave heights of up to 1.25 m. More information on NSL vessels can be found in [22].

NSL has decided not to introduce further vessels of this class as it has acquired two Alnmaritec Wave Commanders which it views as an improvement in offshore wind support.

Figure 4-12: NSL's Celtic Challenger

The vessels were ordered by NSL to improve its fleet of work boats, and it claims that they offer a significant improvement for offshore wind farm servicing. The *Xplorer*, shown in Figure 4-13 has been used at the Barrow offshore wind farm. It achieves a cruising speed of approximately 23 knots, and it is claimed that personnel transfer is possible in significant wave heights (Hs) of 1.8 – 2 m, although, once more, GL GH consider this to be outside of the vessel's normal operating envelope. The larger vessel *Aaryan*, retains the advantages of the *Wave Commander* vessels, but is larger and slightly faster, and has a crane available onboard. *Aaryan* was designed for longer journeys to projects located farther offshore.

Figure 4-13: NSL's *Xplorer* of the Wave Commander Class

Table 4-2: NSL Vessels

Variant	*Wave Train*	*Wave Commander (MK I)*	*Wave Commander (MK II)*
Dimensions	14 m x 5.2 m	15 m x 6 m	18 m x 6 m
Classification	MCA 3	MCA 3	MCA 3
Cruising Speed	18 knots	23 knots	25 knots
Propulsion	Propellers / Jets	Jets	Propellers
Accommodation	Seating for 12, shower, toilet, cooking	Seating for 12, shower, toilet, cooking, TV, computer facilities	Seating for 12, shower, toilet, cooking, TV, computer facilities
Cranage	-	-	Crane available

Offshore Wind Power Marine Services

Offshore Wind Power Marine Services (OWPMS), based in North Wales, UK, has been in the Offshore Wind sector since 2003, when it was contracted during the construction phase of the North Hoyle Offshore Wind Farm. Since then it has contracted vessels for use at North Hoyle, Burbo Bank, Lynn and Inner Dowsing, Rhyl Flats, Q7, Thanet, and others.

Figure 4-14: Workships Contractors B.V.*Offshore Provider*

The *Offshore Provider*, which has assisted in construction activity at the Q7 Project, and shown in Figure 4-14, is the company's first purpose-built offshore wind farm vessel. This vessel is able to transport up to 12 personnel at a speed of approximately 18 knots, and measures 15 m x 6.1 m. More recently, OWPMS has taken delivery of several aluminum work boats of similar proportions and specifications to the *Offshore Provider*.

Turbines are accessed in the same way as for the Windcat and NSL vessels, utilizing a custom-designed detachable bow section which fits to the boat landing. More information on Offshore Wind Power Marine Services can be found in [23].

Turbine Transfers Limited

Also originating from North Wales, UK, Turbine Transfers Ltd is a subsidiary of Holyhead Towing, a tug and support vessel operator working in many oil and gas and renewables sectors in Europe, Africa and the Middle East. Turbine Transfers has a fleet of aluminum-hulled, catamaran work boats all built by South Boats, ranging from 12 m – 20 m LOA.

Figure 4-15: Turbine Transfers' *Rhoscolyn Head*

Work Boat Providers in the U.S.

Recently, Gladding-Hearn Shipbuilding, Duclos Corporation in Massachusetts has begun offering catamaran wind farm work boat vessels to the U.S. market under a license from vessel designer Incat Crowther. Likewise, Blount Boats of Rhode Island has been marketing designs from UK-based South Boats and Lyman-Morse in Maine is working with UK-based Alicat Workboats to provide a series of alternative work boat designs to the U.S. industry.

SWATH Vessels

SWATH (Small Water-plane Area Twin Hull) vessels perform turbine transfers in the same manner as work boats (see Section 4.2.2), but due to their hull design are generally more stable than typical monohull or catamaran vessels. This is due to their specialist hull design which provides the majority of the buoyancy well below the surface, thus minimizing the impact of the vertical motion of the waves on the vessel. For this reason the draft of SWATH vessels tends to be significantly greater than conventional monohull or catamaran vessels. This can cause access difficulties at very shallow sites and harbors and hence may place restrictions on the service base used.

Figure 4-16: SWATH Vessel on Trial

Figure 4-17: German Pilot SWATH Vessel *Dose*

As with work boats, SWATH vessels feature specially designed bows and fenders which are used to dock with the vertical tubular spars of the boat landings to enable personnel to step between the vessel and the structure (note the rubber fender on the bow in Figure 4-18).

Due to their high speeds and inherent stability, SWATH vessels may prove to be cost-effective solutions for wind farms situated in onerous wave climates or relatively far from port. These vessels are currently being trialed at the Bard Offshore Wind Project in the German Bight. Example SWATH vessel providers include Babcock Marine and Aberking and Rasmussen, both of whom design and manufacture SWATH type vessels for military and commercial purposes.

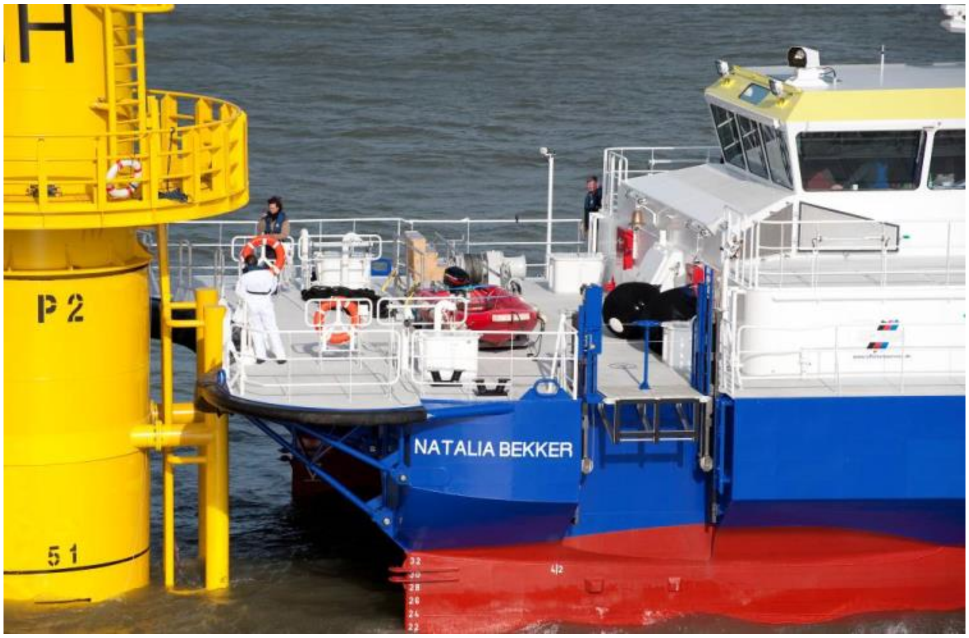


Figure 4-18: Abeking and Rasmussen SWATH Vessel at BARD Offshore Project

Hovercrafts

For access to intertidal regions or areas such as the Great Lakes, where ice coverage is a limiting factor for access during winter months, hovercrafts may add a valuable alternative to traditional floating access. Large and small hovercrafts have been used in the past for crossing large areas of mud or ice, harnessing their ability to travel over areas of both water and land in a fast and maneuverable manner. It is understood that small hovercrafts have been used to good effect for technician transfers during cable laying works in the Wash area of the UK East Coast. In addition, hovercrafts have been used as stand-by rescue craft to allow work to be completed on the construction of Gunfleet Sands Wind Farm, on the Southeast Coast of the UK.

Typically it is expected that hovercraft capacities of 12 passengers or larger will be required in order to provide the sufficient range and endurance anticipated in accessing offshore wind projects. Furthermore, sophisticated variable pitch propellers with the capability for independent control of lift and propulsion would be necessary to ensure safe navigation over or around ice ridges and blocks.

It should be noted that GL GH is unaware of any hovercrafts currently in use for regular O&M activities. Therefore, while hovercrafts are a well tried and tested technology, their use for day-to-day access of offshore installations should be considered new and un-trialed.

Figure 4-19: Hovercraft (courtesy of Griffon Hoverwork [24])

Travelling over rough terrain in hovercrafts can cause skirt damage and hence it would be necessary to factor frequent maintenance intervals in the planning if such a vessel is purchased by the owner, or arrangements for a courtesy vessel to span such intervals if the hovercraft is chartered on a long-term basis.

4.2.4 Helicopter Access

Helicopters have been used for many decades for accessing offshore structures in both civil and military capacities. However, their regular use in the offshore wind sector is still comparatively rare, partly reflecting the relatively early stage of the industry. Currently, helicopters are understood to be in regular use at the Horns Rev Project in Denmark (see Figure 4-20) and the Alpha Ventus Project in Germany. Regulatory approval from the UK Civil Aviation Authority has also been awarded for helicopter hoisting operations to turbines at the under construction Greater Gabbard Project, the first UK project to employ helicopters for the purposes of regular O&M activities.

Source: http://www.aviationtoday.com/photoarchives/rw/75259/

Figure 4-20: Helicopter Hoisting Operation at Horns Rev Offshore Wind Project

The real benefit of accessing offshore turbines via helicopter stems from their inherent insensitivity to wave conditions coupled with the high transit speeds at which they operate. Other meteorological conditions, primarily poor visibility and low cloud base, may restrict operating windows under visual flight rules, but often these occur during relatively benign periods when access can be made by boat anyway. The good accessibility and quick response time offered by helicopters fits well with the relatively high-frequency, low-effort failures which form a large proportion of wind turbine downtime, leaving vessels to attend to the less frequent, larger failures as well as the scheduled maintenance burden.

While project operators are initially met with increased operating costs due to the inclusion of a helicopter, modeling results and industry experience to date indicate that this may be dwarfed by the increase in revenue due to reduced downtime as a result of the lower exposure to weather risk and speedier transit.

Currently, turbine nacelles are too small to allow helicopters to land and hence technicians, small components, and equipment are instead hoisted onto the nacelle from the helicopter while in hover. The level of additional structural steelwork necessary to provide a stable platform sufficiently far from the turbine rotor suggests that landing on nacelles is unlikely to be witnessed in the foreseeable future and hence has not been considered further here.

In the UK and continental Europe guidelines have been produced governing the design of helicopter hoisting platforms on wind turbine nacelles. These ensure that helicopter rotor blades are kept a safe distance from obstructions such as nacelle instrumentation and rotor blades. Prior to hoisting, the rotor will be stopped in either a “Y” orientation or with one blade horizontal (as pictured in Figure 4-21), depending upon helicopter operator preference. The UK guidelines on helicopter hoisting platforms can be found in the Civil Aviation Authority CAP 437 [25].

Source: Bond Air Services of the Bond Aviation Group.

Figure 4-21: Helicopter Hoisting Operation

To date, frequent, offshore helicopter operations have largely been confined to the offshore oil and gas industry. However, offshore wind projects are very different in their requirements. Instead of transporting large groups of technicians to single platforms, offshore wind demands crews of two or three technicians to be transported to many separate structures. For relatively near-shore projects, the dispersed nature of wind farms is well catered for by frequent trips with relatively small aircraft such as the Eurocopter EC135. As projects move farther from land, however, this simple “shuttling” approach becomes less attractive, since increased transit times require larger helicopters with greater endurance and the benefits of rapid response are reduced.

Boat access to turbines is still a necessity even when helicopters are available at a project. Indeed, the rapid, wave-resistant benefits of a helicopter are complimented well by the bulk carrying capacity and insensitivity to visibility provided by work boats. Therefore, as projects move farther offshore, the slow transit times offered by floating vessels will result in a radically different approach to turbine access, whether helicopters are included in a strategy or not. The manner in which helicopters might assist with access to far-shore sites is therefore unavoidably interlinked with the chosen approach to floating access.

A likely outcome of far-shore developments will be the requirement for technicians to live offshore in either fixed or floating accommodation, much like the conventional approach to offshore oil and gas production. This would open up two potential roles for helicopters:

- Transporting crews between the onshore and offshore bases during shift changeovers; and
- Shuttling crews between the offshore base and the turbines.

Clearly, the former of these is suited to larger helicopters with substantial technician carrying capacity, such as the Sikorski S-92 or equivalent, as used for similar operations at existing oil and gas installations. The second role is much the same as that already used at near-shore projects, with one important exception; the aircraft must be stationed and refueled offshore. The use of helicopters to fill these roles once again removes sea-state from the list of limiting factors, which is likely to provide an even greater benefit to the project in such exposed, far-shore locations.

Safety is naturally a preeminent issue contemplated by developers when determining their approach to turbine access and is exacerbated with distance from shore due to the increased response times of land-based search and rescue teams as well as the more onerous conditions. The large area of the North Sea over which oil and gas platforms are installed has led BP to come up with its “Jigsaw” concept, composed of onshore- and offshore-based helicopters as well as multiple vessels all aimed at minimizing rescue times. While such large-scale solutions are unlikely in the offshore wind sector in the immediate future, it may be possible for operators to include a helicopter nominally allocated to O&M activity, in their emergency response plans.

There are substantial regulatory issues to be considered in respect of the routine use of helicopters for accessing offshore wind turbines. Some limitations of helicopters are listed as follows:

- Current turbine size and design prevents landing on nacelle, hence technicians and parts must be winched to a heli-hoist platform.
- Part sizes are restricted (nominally to a maximum of approximately 200 kg for light aircraft, but dependent on project specifics such as flight envelope).
- Offshore re-fuelling on a substation or other fixed structure is subject to environmental and H&S consenting requirements, potentially limiting helicopter range.
- For safety reasons helicopters are required to be able to demonstrate 100% engine redundancy during hoisting operations.
- To ensure the 100% engine redundancy requirement, it is often necessary to temporarily drop one crew off on a substation prior to winching the second crew onto a turbine. The helicopter may then re-collect the first crew for hoisting.
- Wind speed limited to less than 40 – 50 knots during hoisting (often above the maximum wind speed for safe working in a wind turbine nacelle).
- Minimum visibility and cloud base are critical requirements for helicopter operations, typically set to roughly 4,000 m and 200 m, respectively, in the UK under Visual Flight Rules (VFR).
- Discussions are ongoing regarding low-level air access to substations or offshore platforms for crew drop-offs or refueling. It is likely that clear avenues between turbines shall be required to such structures if they are to be used as part of a helicopter strategy and hence the positioning of these structures with respect to turbine locations is likely to be a balancing act between ensuring consent for helicopter operations and limiting electrical losses to substations.

Helicopter Review

Some of the helicopters used to transport technicians to offshore structures include: the Bell 206 L series, the Sikorsky S76 series, and the Eurocopter EC135 series (shown in Figure 4-22). These helicopters typically hold 5 to 13 passengers and are suited to daytime flights over short distances. Their main characteristics are presented in Table 4-3.

Table 4-3: Helicopter Specifications

Specification	Bell 206L4	EC135	Sikorsky S76D
Passenger capacity	1 + 6 PAX	1 + 6/7 PAX	1 + 12/13
Length [m]	12.92	12.16	16.0
Height [m]	3.32	3.51	4.4
Rotor diameter [m]	11.28	10.2	13.4
Cruising speed [km/h]	185-225	254	Up to 287
Range [km]	Up to 623	Up to 620	Up to 818

Brief descriptions of helicopter activities at the Horns Rev and Greater Gabbard Offshore Wind Projects are provided below as case studies.

Horns Rev I

The Horns Rev I offshore wind farm comprises 80 Vestas 2.0 MW wind turbines capable of producing 160 MW. It is located in the North Sea, 14 km west of the West Danish Coast. Currently, Horns Rev is contracting Uni-fly A/S, a Danish-based operator.

Uni-fly uses a Eurocopter EC135 to fly to the offshore platform and turbines at Horns Rev. The helicopter is deployed whenever sea-state prevents floating access or quick transport of personnel and/or parts and equipment are required. More information can be found at [26].

Greater Gabbard

RWE Npower Renewables is currently constructing the Greater Gabbard offshore wind farm in a joint venture with Scottish and Southern Energy. The offshore wind farm is located in the North Sea, 25 km off the Coast of Suffolk, UK. It consists of 140 Siemens 3.6 MW wind turbines capable of producing 504 MW. Bond Aviation Group (Bond), an experienced offshore flight operator in the UK offshore oil and gas sector, has been awarded the first support contract of its kind in the UK, providing helicopter services to Greater Gabbard.

Bond has selected the Eurocopter EC135 to transport personnel, tools, and equipment to the wind turbines. More information can be found in [27].

Source: Bond Air Services of the Bond Aviation Group.

Figure 4-22: EC135 Helicopter for Greater Gabbard Offshore Wind Farm Services

4.2.5 Offshore-based Marine Access

Offshore-based operations are likely to be essential for far-shore projects due to the considerable transit times associated with regular access to these sites. The offshore oil and gas industry has laid the foundations for this approach with the regular use of both fixed and floating offshore accommodation at many well sites. Clearly, however, the demands from offshore wind projects are very different from those of offshore oil and gas platforms, especially in regard to the dispersed nature of wind turbines, where 2-5 technicians may be required on multiple turbines, as opposed to 20+ technicians on one large installation.

Therefore, with offshore-based working in the wind industry, even when technicians are living in the vicinity of the project, the issue of accessing turbines remains. Furthermore, particularly with fixed offshore accommodation, further vessels are typically required to shuttle technicians and parts between the offshore base and the turbines. This can either be achieved by vessels arriving at the platform from a shore-based harbor at the start of the shift or by installing some form of launch and recovery system for deploying and retrieving vessels on and off the base.

Descriptions of the main approaches to offshore-based working are presented in the sub-sections below.

Fixed Offshore Accommodation Platforms

One solution to the issue of sizeable transit times when accessing offshore projects is the use of a fixed offshore accommodation platform on which technicians live for typically 2 – 4 weeks at a time before being replaced at a shift change. Such platforms are relatively well understood structures within the oil and gas industry and typically use either monopile or jacket foundation concepts. There may also be the opportunity to add accommodation to offshore substation(s) associated with an offshore wind project, thereby minimizing the total number of separate structures and potentially cost. However, this can lead to issues relating to the safety of living in close proximity to high-voltage equipment as well as the ease of crane access to such equipment for maintenance purposes.

Currently, Horns Rev 2 in Denmark is the only offshore wind project to be using bespoke fixed offshore accommodation for the purposes of regular O&M activities. For convenience, the accommodation platform has been located immediately adjacent to the offshore substation, such that boat landings, a helipad and some emergency equipment may be common to both structures. Work boats are understood to transit to the offshore platforms from an onshore base, arriving offshore at the start of the shift and thereby maximizing the time available to technicians for working on the turbines.

Figure 4-23: Accommodation Platform (right) and Substation (left) at Horns Rev 2 [28]

It is understood that the helipad on the offshore substation at Horns Rev 2 is used for conveying technicians and parts between shore and the offshore platforms, but that currently access to turbines at Horns Rev 2 is not achieved by helicopter. Such an in-field helicopter “shuttle” service would provide the additional merit of limited impact of sea-state conditions, but is likely to require considerable additional equipment on the offshore platform for the purposes of re-fuelling, maintenance and sheltering, fire-fighting and weather monitoring.

An alternative approach to fixed offshore accommodation is to use a jack-up vessel as an accommodation platform (see Section 4.2.7). This has the benefit of keeping a jack-up vessel on site in case of the need for major component exchange operations, but requires ownership of a jack-up solely for the use of that particular project, which can be costly.

Floating Offshore Accommodation

Offshore accommodation vessels are widely used in offshore oil and gas as well as offshore construction projects and have developed a wide variety of alternative names and characteristics. For the purposes of this review, however, these have been grouped into three primary types:

1. **Floatels** – accommodation vessels which cannot dock directly with offshore structures;
2. **Offshore Support Vessels (OSV)** – accommodation vessels with dynamic positioning capabilities and an access system or gangway to enable direct access to offshore structures; and
3. **Motherships** – accommodation vessels with one or more deployable "daughter crafts" and potentially the added dynamic positioning and access system capabilities of an OSV.

These alternative approaches to offshore-based accommodation and access are described in more detail as below.

Floatels

Floatels are one name given to vessels intended solely for the accommodation of a significant number of personnel. Often converted ferries of cruise ships, these feature luxury, hotel-like accommodation and are kept at anchor within the vicinity of a project as required while retaining the ability to sail to port under their own power for crew changes, restocking or sheltering from storms.

Source: GL GH

Figure 4-24: Floatel *Wind Ambition* used at London Array Phase 1

GL GH is unaware of any floatels on long-term contracts for O&M purposes at a particular offshore wind project; however, it is not uncommon for such vessels to be relied on during construction and commissioning works as well as for concerted maintenance campaigns.

Offshore Support Vessels

Some Offshore Support Vessels (OSV) are likely to be from the offshore oil and gas industry where they perform a wide variety of roles, while a variety of custom-built vessels are also under design, construction, or operational. These vessels are considerably larger than traditional work boats though do not typically accommodate as many technicians as the larger floatels. OSVs are designed to operate in harsh climates and to stay at sea for periods of a week or more. As such, they are fitted with personnel living quarters, kitchen, bathrooms, and entertainment facilities. Such vessels are typically upwards of ~50 m in length, and will require Dynamic Positioning capability with redundancy (DP2 or DP3) to operate in proximity to wind turbines or other offshore structures.

While OSVs do not normally support additional work boats, they may be fitted with specialist access systems (see Section 4.2.6) that facilitate personnel and part transfer to the turbines. It is considered that, should these vessels be utilized at a far-shore or intermediate project, they will stay at the project site for 2 - 4 weeks, before returning to an onshore O&M base for a crew change.

GloMar Offshore Wind Support B.V. is a newly established Dutch company which operates service vessels for the offshore wind industry. GloMar has two new-built Multipurpose Offshore Support Vessels: the *GloMar Typhoon* and the *GloMar Pride*; these vessels are 27 and 42 m in length and are equipped with accommodation facilities for 10 and 16 passengers, respectively. Another example of an OSV is the Noortruck, shown in (Figure 4-25). This vessel has been used at Borkum West II for the deployment of a “bubble curtain” for noise reduction at piling operations.

Source: GL GH

Figure 4-25: *Noortruck* Offshore Support Vessel

Given the early status of far-shore wind energy projects, the number of dedicated offshore wind OSVs is currently very limited with most vessels adapted for a short period before returning to alternative roles in oil and gas and other industries. However, there are numerous designs under development for bespoke OSVs, tailored specifically to the needs of offshore wind O&M, such as the SeaEnergy and Galyna concepts shown in Figure 4-26 and Figure 4-27, respectively.

Figure 4-26: SeaEnergy Marine Offshore Accommodation Concept [29]

Chevalier Floatels is a Dutch-based company with 10 years of experience in the floatel industry. Currently, Chevalier Floatels is developing two state-of-the-art floatels for the offshore wind, and oil and gas industries, the *DP Galyna* (shown in Figure 4-27) and the *Gezina*. The *DP Galyna* is 68 m in length and includes an Ampelmann heave compensated gangway with a reliable DP2 system which transfers the engineers to the wind turbines or platforms; accommodation is possible for 55 passengers (including 13 crew members). During more benign conditions, boat landings for Windcats and support vessels mounted to the hull of such ships can be used to increase their versatility. More information on these types of vessels can be found at [30].

Source: http://www.cfbv.com/vessels.html

Figure 4-27: Chevalier *DP Galyna* Concept with Ampelmann Access System

Motherships

Motherships are purposely designed to support a number of smaller “daughter craft” (typically up to 4, but feasibly more) which are used as the primary transit method to the turbines during relatively calm weather. A launch and recovery system allows these daughter craft to be deployed and retrieved as required. In the simplest cases this takes the form of a deck crane lowering RIBs over the leeward side of the mothership, with a quick-release mechanism to allow each RIB to move off as soon as safely on the water.

This approach fits well with the dispersed nature of offshore wind projects, since multiple crews can be deployed at any given moment, but historically has had limited value to other offshore industries and hence is currently an emerging technology, with minimal experience to date. The principles of motherships and daughter crafts are, however, well tested within the military and emergency rescue sectors, as indicated by the image in Figure 4-28, wherein a RIB is launched from a support vessel.

Source: GL GH

Figure 4-28: Launch of a RIB

In more onerous conditions where safe deployment or transfers using daughter crafts is not feasible, transfers might also be undertaken using specialist access systems installed on the mothership itself, as featured on OSV vessels (see above). However, once again, a fully redundant dynamic positioning (DP2) system would be an essential prerequisite to this. Also like floatels and OSVs, motherships are designed to stay at sea for extended periods and hence are fitted with personnel living quarters, kitchen, bathrooms, and entertainment facilities.

4.2.6 Other Emerging Vessels and Transfer Solutions

The Offshore Wind Industry is currently seeking alternative solutions to the difficulty of obtaining fast, safe, reliable, and weather-insensitive technician and component transfers, especially as far-shore projects in onerous climates are in the pipeline for European offshore development. Naturally, the applicability of these solutions is likely to have a degree of site specificity. Some of these solutions are new systems aimed specifically at access of offshore wind turbines while others are derivatives of access solutions for the oil and gas industry. The solutions detailed in this section are in various stages of development; a few are undergoing prototype production and trialing, while several have not made it beyond the conceptual design stage.

Some of the solutions mentioned in this section are currently being developed with support from the UK Carbon Trust "Offshore Wind Accelerator" (OWA) Access Competition, the shortlisted results of which have been recently published [31]. The OWA Access Competition aims to identify and develop new access systems to improve the availability of turbines and the safety of technicians during the transfer to turbines.

Since the competition in 2010, technical experts from the OWA partners, DNV, and the Carbon Trust have been working with these innovators to de-risk and commercialize their designs.

The shortlisted vessels and transfer solutions as described in the Carbon Trust report are:

- Vessels:
    - TranSPAR crafts [32];
    - Windserver [33];
    - Nauti-Craft [34];
    - Pivoting Deck Vessel [35];
    - SolidSea Transfer [36]; and
    - Surface Effect Ship [37].
- Access Systems and Gangways:
    - Autobrow [38];
    - BMT & Houlder Turbine Access System MK II [39];
    - Momac Offshore Transfer System [40]; and
    - Wind Bridge [41].
- Launch and Recovery Systems:
    - Divex LARS [42];
    - Offshore Kinetics L&R System; and
    - Z Port [43].

These are described in more detail in the following sections (as presented in the Carbon Trust report) together with a selection of other concepts; however, it should be noted that many more such designs and concepts exist and more emerge on a regular basis, and hence the selection discussed here is not exhaustive.

Work Boats and Vessels

Baltec Vessels
Type: Work Boats
Developing Stage: Sea Trialing

Baltec Werft, a German vessel manufacturer, is developing work boats designed for offshore wind turbine operations and maintenance work with wave compensating platforms. The A200E shown in Figure 4-29 is a catamaran type vessel, approximately 20 m in length, and contains seating for up to 12 personnel, kitchen and bathroom facilities, along with a stern-mounted crane for equipment transfer. The vessel is manufactured from a composite material, making it relatively lightweight and fuel efficient, with a cruising speed of approximately 22 knots. It is claimed that the A200E uses half of the fuel of a similar sized aluminum vessels.

Accessing structures from the vessel is performed via a gangway located at the stern of the vessel, and this method has been approved by the MCA during testing at Horns Rev. However, Baltec is also implementing changes to the design which will facilitate access from the bow of the vessel to meet the requirements of its clients, and claims turbine access will be possible in sea-states with a significant wave height of up to 2 m. Baltec is developing both a smaller and larger vessel for similar purposes, although these are currently still in the design phase, and are also able to custom build vessels to meet wind farm operators' specific requirements. More information on Baltec vessels can be found in [44].

Figure 4-29: Baltec *A200E* Undergoing Sea-Trials

TranSPAR Crafts
Type: Vessel and Offshore Hub
Development Stage: Design

The TranSPAR Craft, under development by Extreme Ocean Innovations, is a radically different type of craft when compared to current access vessel design. An extremely small water plane area (buoyant area around the surface of the water), coupled with a fin keel arrangement similar to that found on high performance sailing yachts, has resulted in a very stable transfer vessel especially potentially well-suited for operations in high sea-states. It is understood that the TranSPAR Craft travels relatively slowly with the intention of operating from a central offshore hub specifically aimed at far-shore wind farms in the future. Extreme Oceans Innovation anticipates the concept to be cost-effective from both a manufacturing and operations perspective. More information on the TransSPAR concept can be found in [32].

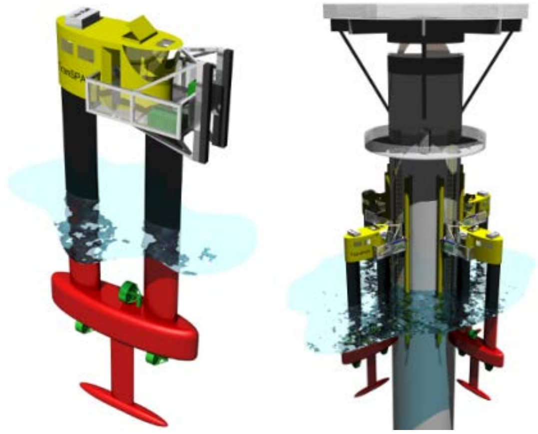


Figure 4-30: TranSPAR Crafts (Extreme Ocean Innovations)

<u>Windserver Vessels</u>
<u>Type: Work Boat Trimaran SWATH Design</u>
<u>Development Stage: In production</u>

The Fjellstrand *WindServer* Trimaran SWATH design allows for very fuel-efficient travel within the wind farm, but unlike other fuel-efficient vessels, the design is intended to increase the stability of the bow of the vessel when stationary, making it ideal for transferring engineers to turbines.

It is understood that the aluminum hulls will be delivered in two sizes: 25 m and 30 m in length, carrying 12 and 24 service personnel respectively, with a cruising speed of 25 knots. Four engine installations powering two controllable pitch propellers are intended to ensure redundancy and flexibility during operation. The vessels will be equipped with ballasting systems to shift between rough weather SWATH mode and light weight transit mode. The design also benefits from considerable foredeck space enabling vessels to carry parts and consumables as well as offering further potential for the addition of a third party access system.

World Marine Offshore has recently secured an order with Fjellstrand for delivery of six of these wind farm vessels. With this new order, Fjellstrand has already made an entry into the offshore wind market. More information on the *Windserver* vessels can be found in [33].

Figure 4-31: *Windserver* Vessels Offered by Fjellstrand

Nauti-Craft
Type: Work Boat
Development Stage: Prototype

The Nauti-Craft is a radical new vessel design currently being pursued by Nauti-Craft Pty Ltd of Australia. The vessel's hulls are separated from the deck and superstructure via a 'passive reactive' hydraulic suspension system. This technology draws on the Nauti-Craft team's experience in the development of interconnected suspension systems used in the motor racing industry. The Nauti-Craft system allows the hulls to conform to the ocean's surface while maintaining the stability of the deck for crew transfers. The concept is also intended to reduce structural loadings while increasing passenger comfort and fuel efficiency. More information on the Nauti-Craft concept can be found in [34].

Figure 4-32: Nauti-Craft

Pivoting Deck Vessel
Type: Work Boat
Development Stage: Design

North Sea Logistics (NSL) is one of the leading offshore wind O&M vessel suppliers and operators (see Section 4.2.3). The Pivoting Deck Vessel concept under development by NSL features a pivoting foredeck, which, when pushed against the boat landing, enables the deck to move independently in pitch from the rest of the vessel. This approach is intended to reduce the relative motion between the deck and offshore structure during transfers. More information on the Pivoting Deck vessels by North Sea Logistics can be found in [35].

Figure 4-33: Pivoting Deck Vessel Concept by North Sea Logistics

SolidSea Transfer
Type: Vessel and bridge system
Development Stage: Design

Robert MacDonald, a student from the University of Strathclyde, UK, is developing a concept for an access vessel and bridge system. The system is intended to improve the safety and stability during transfers onto offshore structures in sea-states above those normally tolerated by regular work boats. The vessel will be reconfigurable offshore in a bid to provide optimal comfort and speed during transfer and subsequent stability and safety during transfers. The concept is at an early stage in the design process and the UK Carbon Trust is supporting the feasibility study to investigate the vessel configuration and confirm its application in the onerous conditions encountered by the offshore wind industry. More information on SolidSea Transfer can be found in [36].

Surface Effect Ship (SES)
Type: Work Boat
Development Stage: Design

This design from Umoe Mandal AS has been adapted from vessels used by the Royal Norwegian Navy as Mine Counter Measure Vessels and Littoral Combat Crafts. It is designed to minimize reliance on surface buoyancy, instead using the principle of an air-cushion, like a hovercraft, to provide sufficient lift to support much of the SES above the waves. The lightweight, composite construction is intended to have the added benefit of high transit speeds so as to make optimal use of weather windows. More information on this new vessel design can be found in [37].

Figure 4-34: Tank Testing of a Model of the Surface Effect Ship

Access Systems and Gangways

Offshore Access System (OAS)
Type: Deployable gangway
Development Stage: Trialing on offshore wind farm / Deployed in offshore oil and gas

Offshore Solutions, a joint venture between Fabricom and AMEC, has developed a telescopic access system for use in the offshore industry. Although it is primarily aimed at the oil and gas industry, there is scope for use in offshore wind turbine access and Offshore Solutions is already offering its system to the offshore wind industry. The OAS system comprises a pedestal crane with a telescopic gangway fitted to the deck of a vessel. Two vertical frame boat landings, 180° apart, are positioned on each turbine foundation, enabling the telescopic boom to be temporarily clamped to either side of the structure depending on the sea conditions. This set-up enables clamping above the splash zone, in an area that is not subjected to ice build-up or marine fouling.

It is understood that the system operates dynamically until the clamped connection is made, at which point the control system is stopped and the structure is free to move in all six degrees of freedom as required to accommodate differences in motion between the vessel and offshore structure. Only then are transfers made.

Figure 4-35 shows the system being deployed from a vessel to an offshore rig. This system is currently in use by the Shell UK and NAM oil and gas business in the southern North Sea, deployed from a purpose-built 72 m vessel. To date the GL GH understands that OAS has not been deployed commercially on any offshore wind project, although trials were performed at the Horns Rev Project in Denmark in 2004. More information on the OAS can be found in [45].

Figure 4-35: Offshore Solutions Offshore Access System

Ampelmann
Type: Motion compensated gangway
Development Stage: Commercially available

Ampelmann Operations BV has developed an access system modeled on the Stewart Platform, an assembly of hydraulically- actuated rams operating in six degrees of freedom. The Ampelmann is designed to be fixed to the deck of a large vessel (ideally more than 70 m LOA). A control system monitors the real-time motion of various accelerometers positioned on the Ampelmann platform and vessel, and uses these measurements to determine the position of the hydraulic rams in order to remove virtually all motion from the platform. In this manner the Ampelmann actively compensates for the motion of the vessel and creates a steady base for personnel and equipment transfer. The transfer is then made across a telescopic gangway attached to the platform. There is a connection between the gangway and the offshore structure. The gangway exerts a force on the structure to keep it in place, as the vessel motions are completely compensated the gangway is steady and standing still.

The Ampelmann system has already been used in support of both installation and O&M activities associated with the offshore wind industry. Examples include assistance during the installation of transition pieces, access during the grouting of monopile structures, and during maintenance of offshore wind farms.

When installed on a large 50 m vessel the system can compensate for motion in up to 2 m significant wave heights. Figure 4-36 shows the Ampelmann system being used to access a wind turbine. More information on the Ampelmann can be found in [46].

Figure 4-36: Ampelmann Motion Compensating Platform in Action [46]

Personal Transfer System (PTS)
Type: Crew lifting system
Development Stage: Final testing

The Personal Transfer System (PTS) is being developed by Personnel Transfer System GmbH. The PTS comprises a remote controlled crane installed on each turbine which lifts the technicians, one at a time, from the vessel to the working deck of the turbine. It also compensates for the motion of the vessel, and the crane control system allows for an automatic transfer of personnel. According to the designers, the limit for safe operation is 500 kg in sea-states up to 3 m Hs, and 800 kg in sea-states up to 1.5 m, allowing it to be used for transfer of large components to the turbine working deck. The concept enables the vessel to maintain a safe distance from the turbine during transfer.

The PTS has passed the prototype phase and is understood to be ready for final testing offshore. During November/December 2007 and January 2008 PTS was tested at a harbor site in Hamburg, Germany. The system developer states that the system can be used in sea-states characterized by significant wave heights of up to 3 m if used in conjunction with a large vessel. Figure 4-37 shows the PTS concept during trials in Hamburg, Germany. More information on the PTS concept can be found in [47].

Figure 4-37: PTS during Testing in Hamburg [47]

FROG and the Offshore Wind Access System (OWAS)
Type: Personnel transfer pod
Development Stage: In use in the oil and gas industry and under development for the offshore wind industry.

The FROG, developed by Reflex Marine and shown in Figure 4-38, is a buoyant personnel transfer capsule which is transported using a standard deck crane. Some contractors within the oil and gas industry employ the FROG for vessel-to-vessel and vessel-to-installation transfers. It can transfer up to nine personnel, with light equipment and tools, per lift, and is designed to protect crews against any vertical and lateral impacts which might occur during transfer. The concept enables the vessel to maintain a safe distance from the turbine during transfer. The FROG was proposed to be used at the Arklow Bank Offshore Wind Farm in Ireland, but operational issues with the remotely controlled crane prevented the system from being implemented.

Reflex Marine is now proposing a smaller, lighter personnel transfer capsule that can be easily stowed on a workboat, combined with a specially-built turbine crane. This system, known as the Offshore Wind Access System (OWAS), is a simpler utilization of the FROG specifically for offshore wind purposes. An advantage of this system is that it can be used in conjunction with small work boats. Figure 4-39 shows the OWAS concept in use at a wind turbine platform. More information on the FROG can be found in [48].

Figure 4-38: Reflex Marine, FROG-3 Crane Transfer Trials on Main Pass 41 in the Gulf of Mexico

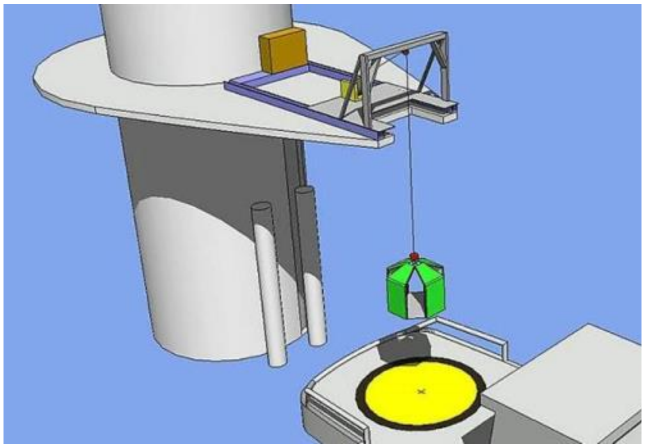


Figure 4-39: Reflex Marine, OWAS Proposed System

<u>MaXccess Transfer System</u>
<u>Type: Platform with motion compensation</u>
<u>Development Stage: Commercially available</u>

Developed by Northumberland-based OSBIT Power Limited, MaXccess has been chosen for use at the Sheringham Shoal Wind Farm on the UK East Coast, following a series of sea trials, including at Statoil's Hywind demonstration floating wind turbine in Norway. MaXccess is a device which may be mounted to the foredeck of most work boats. It clamps onto either of the vertical tubular spars of the boat landing (see Section 4.2.1) and allows the vessel to roll, pitch and yaw freely, while preventing vertical and horizontal bow motion. The connection is created without the need for active compensation or complex control software. A small, stepped gangway then provides direct access to the ladder. More information on the MaXccess Transfer system can be found in [49].

Figure 4-40: MaXccess Transfer System, OSBIT Power

The Windlift
Type: Suspended Platform
Development Stage: Prototype

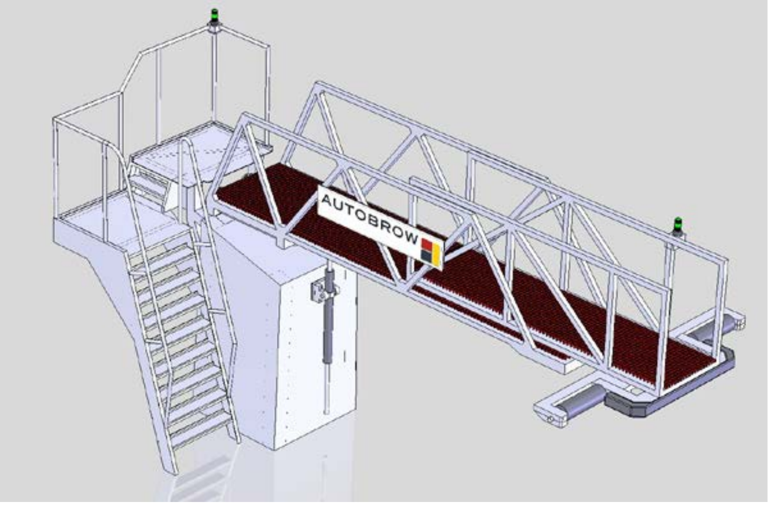
The Windlift system, developed by Fassmer, is a height-adjustable platform for access to offshore wind turbines from small, floating vessels. Personnel and equipment are transferred to the platform at vessel-deck level. The platform, which is fitted around the turbine foundation, is then hoisted to the working deck level, avoiding the need for technicians to climb external ladders. The Windlift concept and prototype are shown in Figure 4-41. More information on the Windlift can be found in [50].

Source: Fassmer website

Figure 4-41: Windlift Platform, Fassmer

Autobrow
Type: Work Boat and bridge system
Development Stage: Design

Designed by Ad Hoc Marine Designs, developed by Otso Ltd, and supported by work boat supplier South Boats, the Autobrow is an actively compensated gangway system designed to be lightweight, reliable and flexible, which can be retrofitted to existing vessels with no requirement for vessel or boat landing modifications. Vertical active compensation from a hydraulic system is intended to remove the effects of heave and pitch while passive mechanisms are understood to allow the gangway to compensate for roll to a limited extent. More information on the Autobrow Concept can be found at [38].



Source: Autobrow

Figure 4-42: Autobrow Design Scheme

BMT & Houlder Turbine Access System (TAS) Mark II
Type: Bridge system
Development Stage: Prototype

This transfer system is a development of the award-winning TAS® system, developed by Houlder with BMT Nigel Gee. The device can be fitted to small vessels without the need for dynamic positioning capabilities. TAS is understood to utilize a system of damped rollers and active compensation to reduce the differential motion between the vessel and offshore structure. In this manner, reliance on the standard friction grip between the vessel and boat landing is avoided. More information on the TAS Concept can be found at [39].

Source: http://www.bmt.org/?/51/40/2870

Figure 4-43: BMT & Houlder Turbine Access System

MOTS (Momac Offshore Transfer System)
Type: Bridge system
Development Stage: Sea Trialing

This design, based on an industrial robot arm, uses a variety of accelerometers to measure the motions of the vessel and compensates by adjusting the position of the arm to keep the transfer platform stable. It is understood that the device can operate in conjunction with work boats if a roller system is fitted to maintain a constant lateral distance between vessel and boat landing or alternatively a dynamically positioned vessel may be used. The design is currently undergoing prototype testing. More information on the MOMAC offshore transfer system can be found in [40].

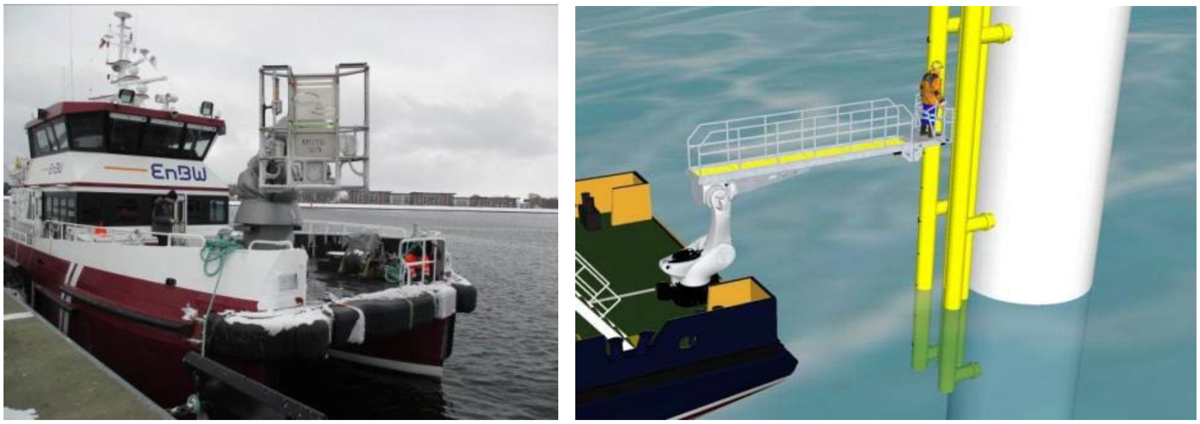
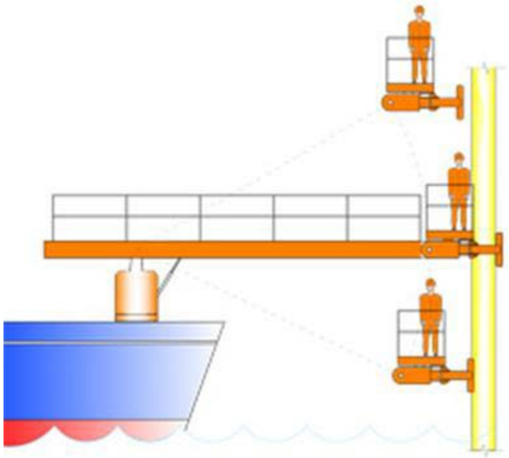


Figure 4-44: MOTS 500 (left) and MOTS – G (right), MOMAC Offshore Transfer System

Wind Bridge
Type: Bridge system
Development Stage: Design

Wind Bridge is an access gangway which uses a system of pneumatics to absorb impacts and provide active heave compensation. Once in position, the end of the gangway is clamped to part of the boat landing structure and personnel are free to transfer. More information on the Wind Bridge can be found in [41].



Source: Knud E. Hansen

Figure 4-45: Pneumatic-based Wind Bridge

Launch and Recovery Systems

Divex LARS
Type: Launch and Recovery system
Development Stage: Design

Drawing from its experience in the commercial diving industry, Divex has put forward two approaches for the launch and recovery of daughter craft from motherships in support of offshore-based working (see Section 4.2.5). The approaches use either a recovery ramp of floating dock to enable quick response craft or work boats, respectively, to be deployed and recovered. It is understood that both concepts use variable-buoyancy cradles and winch systems to account for wave motion during operation. More information on the Divex LARS concept can be found in [42].

Offshore Kinetics L&R system
Type: Launch and Recovery system
Development Stage: Design

Offshore Kinetics is developing a complete system in support of offshore-based O&M. The concept includes a mothership, multiple daughter crafts, launch and recovery system, and personnel accommodation facilities as well as a system for moving and stowing daughter crafts on the deck. It is understood that the concept is still at an early stage and hence limited information is available at the time of writing.

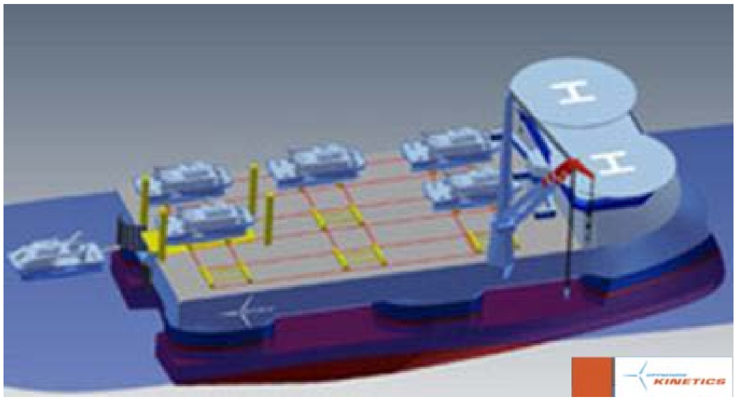


Figure 4-46: Launch and Recovery System by Offshore Kinetics

Z Port
Type: Launch and Recovery system
Development Stage: Design

Z Technologies are developing four technologies associated with offshore access, the Z-Port, Z-Lift, Z-Catch, and Z-Bridge, the details for which can be found at [43]. The Z-Port was selected as a shortlisted technology by the Carbon Trust for the launch and recovery of daughter crafts. The concept consists of a mothership, stationed in the vicinity of the wind project, with accommodation for up to 90 technicians and 20 support crew. Deployment and retrieval of daughter crafts is performed within the “harbor” at the stern of the mothership, which is oriented away from the wave direction. The harbor features an area of 85 m by 15 m of water within which the wave height is reduced due to the sheltering effect of the vessel. The daughter crafts are understood to be launched and recovered using cranes around the harbor area. More information on the Z Port by Ztechnologies can be found in [43].

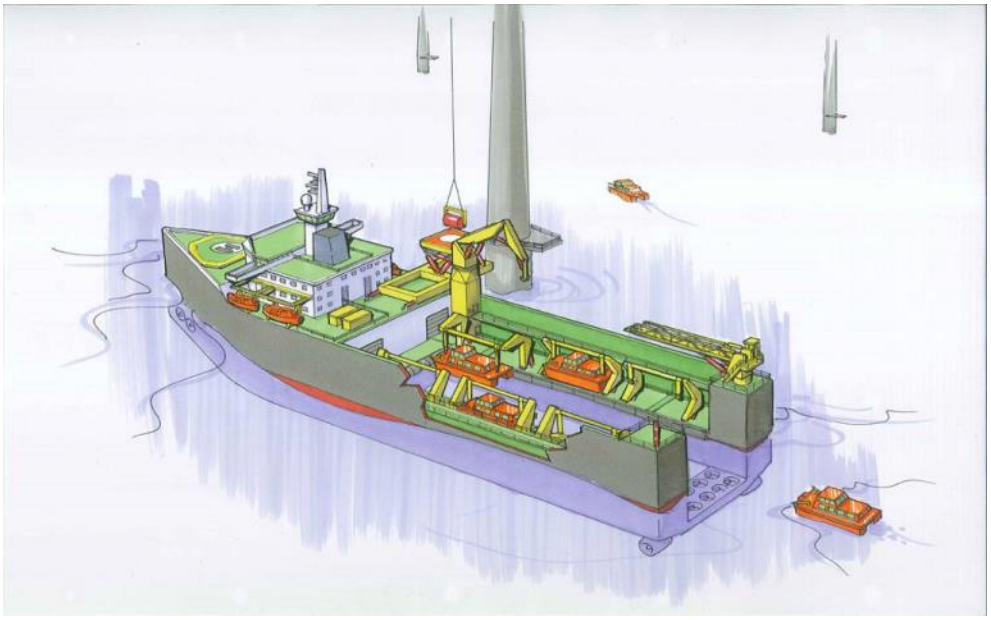


Figure 4-47: Z Port by Z Technologies

Amphibious and Ice-crossing Vessels

To date few large-scale offshore projects have been constructed in regions where floating ice is a regular occurrence and hence relatively little effort has been made to develop methodologies to enable access during ice coverage. However, given the significant maintenance burden associated with wind power projects, such access is deemed essential for any commercial-scale projects in regions subjected to ice coverage for more than a week or so per year. Perhaps the most developed approach to crossing regions of floating and pack ice is the hovercraft, as discussed in Section 4.2.3. However, other amphibious vehicles exist which may provide a good access solution during periods of partial or complete sea ice coverage. Like many of the concepts discussed in this section, these vessels have a limited track record in commercial use and hence should be carefully assessed before access strategies are designed which depend upon them.

Historically, several companies have proposed construction machines with “screw-threaded” propulsion systems for operating on soft sandy seashores, and mud banks in inter-tidal regions. These machines were envisaged to utilize the hydraulic track-motors from excavator or bulldozer tracks and have large diameter floatation devices fitted with augur-fins, based on bulldozer grouser bars to provide propulsion. It is understood that similar machines have been designed and operated in sea ice conditions.

Airboats may also provide transport over areas of ice or sea, but it is anticipated that these will be constrained to relatively flat ice and calm seas. Figure 4-48 and Figure 4-49 show example amphibious craft used in the past when traversing large areas of ice and water.

Figure 4-48: Airboat being Trialed on Sea Ice [51]

Figure 4-49: Example of Tracked Amphibious Vehicles [52]

4.2.7 Jack-Up Vessels

Nacelle-based davit cranes and lifts within turbine towers are heavily constrained by the size and weight of any lifted load, rarely exceeding ~2 tons. Clearly, many major component exchange operations within turbine nacelles can exceed such loads and sizes and hence external cranage mounted on jack-up or leg-stabilized vessels are required. The only exception to this might come with floating turbine technology wherein the turbine might itself be lowered or towed to port due to water depths exceeding jack-up capabilities.

Jack-up and leg-stabilized vessels have been in use in the marine construction and offshore oil-rig maintenance and conversion marketplaces for many years. These vessels come in a range of shapes and sizes with 3 – 6 legs and self-propelled or towed, in addition to featuring a wide variety deck layouts and capacities, crane capabilities and water depth limitations. Ultimately, however, for the purposes of offshore wind O&M works, it is the stability provided by the legs which is of critical importance. This is due to the significant heights of modern turbines which necessitate a high degree of stability during lifting operations to limit sway in the lifted components.

Source: GL GH

Figure 4-50: Hotchief's *Odin* Jack-Up Vessel Positioning next to a Turbine

Many jack-up vessels are fitted with permanent cranes, but since they are often designed to be customized for each new site, existing cranes may be upgraded within the limits of the leg-jacking and deck bearing capacities. Therefore, the following are prerequisites during major replacements works at offshore wind installations:

- Stable platform (either jack-up or leg-stabilized vessel);
- Sufficient leg length for water depths (vessels currently available for work in the range of around 5 m – 90 m water depths);
- Sufficient crane boom length to reach turbine nacelle with ample under-hook height and distance between vessel and turbine;
- Lifting capability (at the above boom reach) for ~500 tons or more (depending upon operation); and
- Access (including leg clearance) to site.

Beyond the above requirements, most technical differences between vessels for performing major replacements operations are dwarfed by the commercial availability of such vessels, which can easily result in lead times of many weeks depending on the contracting strategy undertaken. In general, ownership of a jack-up barge by the project owner or developer is likely to result in the shortest lead time, which could be as little as 3 days for basic mobilization and transit activities. Clearly this will minimize turbine downtime; however, the benefit of reducing lost production comes as a trade-off with the high costs associated with buying and running a jack-up barge.

On the open market, jack-ups can be contracted when they are required, the benefit being that all responsibility of financing the purchase and operating the barge do not lie with the wind farm owner or operator. However, open market approaches generally have the longest lead times (often in excess of four weeks) as the wind farm operator will have to wait for the vessel to finish another job, re-mobilize, and transit to the site.

A compromise option between these two strategies is to adopt a call-off contract or sharing scheme with an independent jack-up operator whereby an annual retainer is paid to ensure shorter lead times than on the open market approach and potentially less variable day-rate costs. This approach is often achieved through the owner or operator owning a jack-up vessel across a portfolio of several offshore projects.

If a jack-up vessel is to be owned specifically for a given project, then the operator may consider its auxiliary use as offshore accommodation (see Section 4.2.5). Access to turbines could then be carried out via work boats assumed to transit to the jack-up prior to the start of the working shift. To achieve this, the jack-up could be nominally stationed adjacent to a turbine, substation, or other structure and hence may utilize the boat landing belonging to that structure for transferring technicians between the jack-up and work boats.

Source: GL GH

Figure 4-51: *MPI Resolution* 6-leg, Self-propelled Jack-up

To date in the offshore wind industry, access limitations associated with the beam, height, and draft of jack-up vessels have led to the exclusion of some ports, but have not historically proven to be a constraint for site access. However, large vessel access to any offshore wind farms located within the Great Lakes would automatically be more restricted, unless these vessels are locally constructed or sourced. Any vessels not native to the Great Lakes must enter from the Atlantic via the Great Lakes St. Lawrence Seaway System. The vessels that can use the Seaway system are limited by the size of the locks that form the Seaway. The maximum allowed vessel size for the system is 225.6 m length, 23.8 m beam, and 8.1 m. This maximum permissible vessel size is informally known as the Seawaymax and is of vital importance draft when considering this region.

Current numbers of available jack-up vessels which meet the Seawaymax requirements are very limited (largely by beam) and include:

Table 4-4: Jack-Up and Lifting Vessels Able to Navigate the Great Lakes St. Lawrence Seaway System

Company	Name of Vessel	Type	Beam [m]
A2SEA	*SeaEnergy*	Leg-Stabilized Vessel	21.6
A2SEA	*SeaPower*	Leg-Stabilized Vessel	21.6
Besix	*Pauline*	Jack-up Vessel	23.5
DBB Jack-Up	*Wind*	Jack-up Vessel	18.0

4.3 Summary of Vessels and Access Methods

The access methods, vessels, and concepts detailed in Section 4.2 are in various stages of development. Despite a wide range of emerging approaches, most currently operational projects have adopted the standard turbine access method of stepping from a marine vessel directly to the turbine ladder as outlined in Section 4.2.2.

However, despite the good safety record that has been maintained to date, it is evident that there is scope for improvement, both in terms of the accessibility of offshore structures and in the safety of the access methods adopted to achieve such access. The market is responding to the potential risks of current access methods and the reduction of revenue that results from poor accessibility, while the slow evolutionary improvement in work boat access is becoming interspersed with the adoption of more revolutionary solutions, as some projects start to embrace helicopters, offshore-based working, SWATH vessels, and sophisticated access systems. As projects are situated farther from port and in more onerous conditions, these trends are likely to continue, with developers seeking to identify approaches which best suit their projects in terms of both direct costs and project revenue.

The vessels presented in Section 4.2 are summarized in Table 4-5. Note that the capability, stated here in terms of significant wave height (Hs), is purely indicative based upon supplier information and, where available, industry experience. As previously commented, the limiting factor for access capability is primarily wave height, but factors such as current, wind speed, wave period, water depth, localized wave effects, wave direction, ice, and visibility are also important parameters.

Table 4-5: Summary of Vessels for Offshore Turbines Access

Vessel	Development Stage	Type	Advantages	Disadvantages	Hs Limit [1]
Quick Response Vessel	In commercial use	Rigid Inflatable Boats (RIB)	• Provide fast access to the site • Widely available in the market • More fuel efficient than most work boats • Potential for use as daughter craft	• Unsuitable for transit over large distances • Unsuitable for transit in onerous conditions • Unsuitable for transferring spare components and consumables larger than ~50 kg	~ < 1.0 m (2)
Workboat	In commercial use	Aluminum or Composite Catamarans	• Operational experience • Can lease vessel on long-term basis • Widely available in the market • Large work boats can accommodate lifting equipment • Potential to accommodate some access systems	• Personnel facilities and comfort make it unsuitable for transfers longer than ~ 2 h.	0.6 - 1.5 m (2)
SWATH Vessel	In commercial and military use	Small Water-plane Area Twin Hull (SWATH) Vessel	• Vessels already in use for commercial and military applications • More stable vessel may facilitate personnel transfer in more onerous conditions • Passenger comfort during transit improved compared to mono-hulls / catamarans • Can accommodate medium-size spare parts • Potential to accommodate some access systems	• Expensive • Large vessel draft	1.0 – 2.0 m (3)

Vessel	Development Stage	Type	Advantages	Disadvantages	Hs Limit [1]
Floatel	In commercial use	Converted ferry or small cruise ship	• Large • Plenty of luxury accommodation • Comfortable and stable • Can remain offshore for extended periods	• Expensive capital and running costs • Large vessel draft • No direct access to offshore structures • Dependent on smaller vessels for transfers	N/A
Offshore Support Vessel (with a basic gangway)	In commercial use	Large work boats	• Large number available within oil and gas sector • Large vessel may facilitate personnel transfer in more onerous conditions • Can remain offshore for extended periods • Potential to accommodate most access systems • Dynamic positioning	• Expensive capital and running costs • Large vessel draft	1.0 – 1.5 m (2) (with a basic gangway arrangement)
Mothership (with a basic gangway)	Adaptable from vessels in commercial use / concept	Mothership	• Custom-made / adapted vessels with most of the equipment required for offshore wind O&M services • More stable vessel may facilitate personnel transfer in more onerous conditions • Equipped with Quick Response Vessels or small Work Boats. • Can stay offshore for extended periods • Can accommodate medium size spare parts • Can accommodate access system	• Expensive capital and running costs • Large vessel draft	1.0 – 1.5 m (2) (with a basic gangway arrangement)

Vessel	Development Stage	Type	Advantages	Disadvantages	Hs Limit [1]
Hovercraft	In commercial and military use	Hovercrafts	• Enables access during periods of partial and complete ice coverage • Enables access in intertidal regions • Provide fast access to the site • Possible to be stored and maintained on land	• Heavy maintenance burden • More limited by wind speed and significant wave height conditions than work boats	~ < 1.0 m (2)
Helicopter	In use	Helicopter hoist to turbine nacelle	• Operational experience • Can lease helicopter on long or short term basis • Can operate in any sea conditions • Short transit times • Suitable for far offshore projects • Fits well with dispersed nature of offshore wind projects	• Expensive • Requires winching area on nacelle of each turbine • Only suitable for diagnosis, small component repairs and minor faults • Possible regulatory / consenting restrictions	N/A (wind speed limit ~40 knots; visibility > ~4 km)
Jack-up	In use	Jack-up vessel or barge	• Suitable for all types of repairs (small to large components) • Heavy lift capabilities • Accommodation facilities for technicians • High stability after jacked • Can remain offshore for extended periods	• Expensive capital and running costs • Slow transit speeds • Slow to position and jack-up • High demand in offshore wind and other industries leading to long lead times • Wave height and current limited during jacking	1.0 – 2.5 m (2) (during jacking)

1. Assuming standard turbine access, involving crew stepping from vessel bow to turbine ladder while vessel is driven against turbine, unless otherwise stated.
2. GL GH estimate based on manufacturer or supplier claims and/or operational experience. Does not account for wave period, current, wind, or other access criteria.
3. GL GH estimate. Does not account for wave period, current, wind, or other access criteria.

5 METOCEAN CONDITIONS ANALYSIS

5.1 Wind Speed and Significant Wave Height Time-Series

As described in Section 2, for the Atlantic Coast, Pacific Coast and Gulf Coast regions, wind speed and significant wave height time series data were sourced from the NOAA WAVEWATCH III hindcast model. These data are available in a 3-hour temporal resolution and have been linearly interpolated to 1-hour resolution as required by the GL GH in-house O2C and O2M models. For the Great Lakes region, data were sourced from a combination of NDBC [4] buoy data and shore-based wind station data in Lake Michigan, which is already in a 1-hour resolution.

In order to enable the O2C and O2M models to analyze the performance of activities within variable metocean conditions across each of the eight defined regions, the three sourced time series of each region were processed as follows:

1. For each coastal region, the long-term (11 years) mean significant wave height (Hs) and mean wind speed across all three climates were identified.
2. Each of the three time series were scaled to these identified mean Hs and mean wind speed values for that region.
3. The three scaled time series were stacked together to make one single 33-year time series for each region, with the exception of the Great Lakes region where the long-term time series comprised 10 years of data and therefore originated a 30-year time series.
4. In order to cover a wide range of metocean climates, a range of metocean conditions was estimated per coastal region. This range was estimated based upon the mean significant wave height of the region and followed the process below:
    - 4.1 The minimum mean significant wave height was assumed to be the lowest long-term (11 years) mean significant wave height recorded by any of the data locations across all regions of that ocean / gulf / lake minus 10% to account for extreme conditions (e.g. for the Atlantic South region, the lowest mean significant wave height across the Atlantic North, Central and South was used).
    - 4.2 The maximum mean significant wave height was assumed to be the highest long-term (11 years) mean significant wave height recorded by any of the data locations across all regions of that ocean / gulf / lake plus 10% to account for extreme conditions (e.g. for the Atlantic South region, the highest mean significant wave height across the Atlantic North, Central and South was used).
    - 4.3 The average of the mean significant wave heights in Steps 4.1 and 4.2 was used as a central value.
5. The 33-year significant wave height time series of each coastal region were scaled to the 3 alternative values described in Step 4, resulting in three long-term (33-year) time series for each coastal region with a maximum, central, and minimum long-term mean.
6. A correlation between mean wind speed and mean significant wave height for each region was used to inform the scaling of the 33-year wind speed time series to match the significant wave height time series derived in Steps 4.1 to 4.3 above.
7. This resulted in 24 metocean climates defined by 33-year significant wave height and wind speed time series. The mean significant wave height and mean wind speed of each 33-year time series are given in Table 5-1.

This approach provides a broad statistical spread of historical data for each region while retaining local seasonal and persistence trends unique to that region. Both O2C and O2M models run through each time series in the time domain on an hour-by-hour basis and record the long term, converged results using the full 33-year period. On this basis, the final time series have the following merits:

- Combining three independent, non-sequential time series simply provides a greater statistical basis to the modeling.
- By keeping each original time series to an integer number of years, seasonal trends are retained once combined.
- Persistence and exceedance characteristics from three spatially separated locations in each region are captured to provide a good approximation of long-term trends and characteristics right across that region.
- The long-term mean conditions to which the time series were scaled for each region were selected to best represent reasonable min, max, and average long-term mean conditions and hence provide a good basis for interpolation of the modeled results to a wide variety of alternative mean conditions for each coastal region.

Table 5-1: Summary of Final 33-year Processed Time Series

Coastal Region	Range	Average Significant Wave Height [m]	Average Wind Speed @ 10 m MSL [m/s]
Atlantic North	Min	0.59	5.1
	Central	1.26	6.5
	Max	1.93	7.9
Atlantic Central	Min	0.59	5.1
	Central	1.26	6.5
	Max	1.93	7.9
Atlantic South	Min	0.59	5.1
	Central	1.26	6.5
	Max	1.93	7.9
Gulf of Mexico East	Min	0.77	5.3
	Central	1.23	6.6
	Max	1.68	7.9
Gulf of Mexico West	Min	0.77	5.3
	Central	1.23	6.6
	Max	1.68	7.9
Pacific South	Min	1.71	5.3
	Central	2.25	6.3
	Max	2.79	7.3
Pacific North	Min	1.71	5.3
	Central	2.25	6.3
	Max	2.79	7.3
Great Lakes	Min	0.55	5.8
	Central	0.73	6.3
	Max	0.91	6.8

5.2 Ice Coverage Time-Series (Great Lakes Region)

As mentioned in Section 2.3, daily Great Lakes ice cover grid time series were created for each winter season by interpolating between observed ice chart grids from the NOAA Great Lakes Ices Atlas [5].

6 INSTALLATION MODELING ASSUMPTIONS

6.1 Installation Modeling Options

After reviewing current, emerging and proposed future installation methodologies, as described in Section 3, GL GH has conducted a high-level assessment of the suitability of these installation methodologies, considering U.S. specific site conditions and the potential development of the U.S. offshore wind market.

The review of each installation methodology focused on the following:

- Level of Standardization: Is the method proven and is there experience with its application?
- Installation Plant Availability: Are existing vessels and installation equipment, both inside and outside the U.S., suitable for this method and widely available?
- Installation Costs: how expensive is the charter of the installation plant?
- Weather Sensitivity: how sensitive is the method to weather conditions?
- Port requirements: how significant are the requirements on the ports, and how likely is this to be achieved with existing infrastructure?

Each of the above criteria has been scored using a Low (L), Medium (M) or High (H) score, where High corresponds to a method which is well proven within the offshore industry (considering experience in Northern Europe) and likely to be available in the U.S. without the requirement for significant investment in plant or infrastructure. Low is a relatively unproven method which will require significant investment.

Table 6-1 presents the results of the high-level review. Scores have been derived for each of the installation methodologies, considering the following scoring mechanism:

- Low = 1;
- Medium = 2; and
- High = 3.

Scores for each of the above criteria have been summed to provide a method of comparing the relative proveness, or maturity, of the installation methodology based on experience in Northern Europe.

Existing installation methodologies which have a combined score above 8 have been taken forward and highlighted in green, as these are considered to be at a level of proveness or maturity to consider them applicable to the emerging U.S. Market. In the case of gravity base structures, where none of the methodologies score above 8, the two highest scoring installation approaches have been taken forward.

Novel installation methodologies have been discounted from the above technical scoring exercise, given the unique nature of each concept, which prohibits comparative scoring. Instead, novel methodologies have been taken forward which differ to a significant extent from existing concepts where foundations and wind turbines are installed in separate operations. Two novel methodologies have therefore been taken forward which demonstrate a combined foundation / wind turbine installation concept. One of these concepts requires the utilization of a bespoke installation vessel while the other considers a floating foundation solution.

Table 6-1: Proposed Installation Methodologies for Modeling

No.	Installation Methodology	Level of Standardization	Equipment Availability	Installation Costs	Weather Sensitivity	Port Requirements	Overall Score
	Foundation Installation						
1	Jackets - pre-installed driven pin-piles - installation vessel transports foundations	M	L	M	L	H	9
2	Jackets - pre-installed driven pin-piles - feeder vessel transports foundations	M	H	H	M	H	13
3	Jackets - pre-installed drive/drill/drive pin-piles - installation vessel transports foundations	M	L	M	L	H	9
4	Jackets - pre-installed drive/drill/drive pin-piles - feeder vessel transports foundations	M	M	H	M	H	12
5	Jackets - pre-installed drilled pin-piles - installation vessel transports foundations	M	L	M	L	H	9
6	Jackets - pre-installed drilled pin-piles - feeder vessel transports foundations	M	M	H	M	H	12
7	Jackets - post-installed driven pin- piles - installation vessel transports foundations	M	L	M	L	H	9
8	Jackets - post-installed driven pin-piles - feeder vessel transports foundations	M	H	H	M	H	13
9	Jackets - post-installed drive/drill/drive pin-piles - installation vessel transports foundations	M	L	M	L	H	9
10	Jackets - post-installed drive/drill/drive pin-piles - feeder vessel transports foundations	M	M	H	M	H	12
11	Jackets - post-installed drilled pin-piles - installation vessel transports foundations	M	L	M	L	H	9
12	Jackets - post-installed drilled pin-piles - feeder vessel transports foundations	M	M	H	M	H	12
13	Monopiles - driven pile - installation vessel transports foundations	H	M	M	H	H	13
14	Monopiles - driven pile - feeder vessel transports foundations	H	H	H	M	H	14
15	Monopiles - driven pile - float-out transport of foundations	M	H	H	L	H	12
16	Monopiles - drive/drill/drive pile - installation vessel transports foundations	H	M	M	H	H	13
17	Monopiles - drive/drill/drive pile - feeder vessel transports foundations	H	H	H	M	H	14
18	Monopiles - drive/drill/drive pile - float-out transport of foundations	M	H	H	L	H	12
19	Monopiles - drilled pile - installation vessel transports foundations	H	M	M	H	H	13
20	Monopiles - drilled pile - feeder vessel transports foundations	H	H	H	M	H	14
21	Monopiles - drilled pile - float-out transport of foundations	H	H	H	L	H	13
22	Gravity base structures - float-out transport of foundations	L	M	H	L	L	8
23	Gravity base structures - feeder-barge vessel transports foundations	M	M	M	L	L	8
24	Gravity base structures – semi-buoyant lift installation of foundations	L	L	L	L	L	5

No.	Installation Methodology	Level of Standardization	Equipment Availability	Installation Costs	Weather Sensitivity	Port Requirements	Overall Score
	Wind Turbine Installation						
1	Wind Turbine - single blade - multiple tower sections - installation vessel transports turbines	H	H	M	M	H	13
2	Wind turbine - 'Bunny ears' - multiple tower sections - installation vessel transports turbines	M	L	M	M	L	8
3	Wind turbine - full rotor - multiple tower sections - installation vessel transports turbines	M	M	M	M	M	10
4	Wind turbine - complete wind turbine - installation vessel transports turbines	L	L	H	M	M	9
5	Wind turbine - feeder vessel transports turbines	L	M	M	L	M	8
	Inter-array & Export Cable Installation						
1	Ploughed cable installation	H	H	H	M	H	14
2	Jetted cable installation	M	H	H	M	H	13
3	Trenched cable installation	M	M	H	M	H	12
	Offshore Substation Installation						
1	Monopile or jacket foundation followed by substation topside	H	H	M	M	M	12
2	Combined foundation and topside - self-installing (WIPOS by Siemens)	L	L	M	M	M	8

Table 6-2: Proposed Novel Modeled Installation

	Novel Installation Concepts	Level of Standardization	Equipment Availability	Installation Costs	Weather Sensitivity	Port Requirements	Overall Score
1	Monopile foundation installation - concrete drilled	-	-	-	-	-	-
2	Monopile foundation installation - suction bucket	-	-	-	-	-	-
3	Multi-pile foundation installation - piled installation (BARD Tri-pile)	-	-	-	-	-	-
4	Multi-pile foundation installation - suction bucket (SPT Offshore & Wood Group)	-	-	-	-	-	-
5	Jacket foundation installation - self installation float out (MARCON)	-	-	-	-	-	-
6	Gravity base foundation installation - combined foundation and wind turbine installation	-	-	-	-	-	-
7	Floating foundation installation	-	-	-	-	-	-

6.2 Modeling Approach

6.2.1 Optimization of Offshore Construction (O2C) Model

GL GH has developed an analytical, simulation-based approach known as the O2C Model in order to simulate the build-out of offshore wind farms. The O2C Model provides robust estimates of construction downtime due to operational constraints in order to develop a realistic build schedule. The model takes into account the predicted climatic conditions at the site and assumptions regarding the durations and weather limitations for offshore operations (where an operation might be lifting a wind turbine nacelle into position on the tower). Operations are collated into a sequence of activities to estimate the total wind farm project build. Figure 6-1 shows a simplified block diagram of the O2C Model.

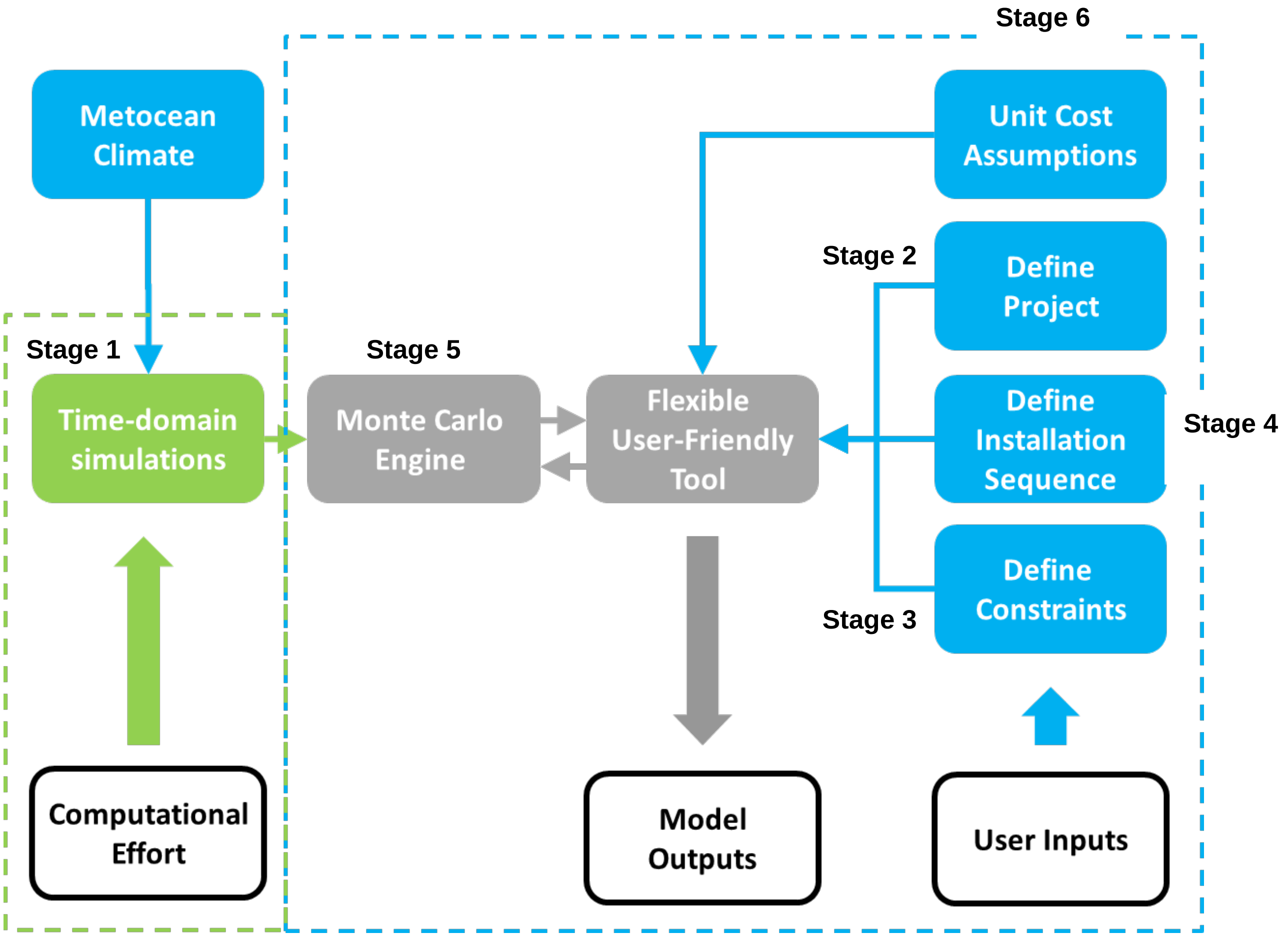


Figure 6-1: Simplified Block Diagram of the O2C Model

The following sections describe the various stages to the O2C modeling exercise conducted for the Installation and O&M LCoE Analysis Tool.

6.2.2 Stage 1: Time-domain Modeling of Offshore Operations

Stage 1 has been undertaken by GL GH in-house due to the computer-intensive nature of this part of the modeling.

GL GH has developed 24 metocean climates covering the U.S. Atlantic and Pacific coastlines, as well as the Gulf of Mexico and the Great Lakes, as described in Section 2. The O2C Model has been used to simulate the execution of generic installation operation durations and operation metocean limitations against these 24 metocean climates. To capture all typical offshore operations, a range of parameters have been taken forward, as defined in Table 6-3. These parameters cover typical values for generic installation operations, while capturing instances where activities require an uninterruptible weather window (Continuous) and where activities can be interrupted by weather downtime (Broken). Every combination of these parameters has been modeled.

GL GH has assigned the maximum Ideal Activity Duration (excluding weather downtime) as 168 hours (1 offshore working week), with the assumption that any one single sub-operation duration would not exceed this value. If this situation were to arise it should be possible to combine sub-operations in order to emulate a longer duration.

Table 6-3: Modeled Activity Durations and Weather Limitations

Ideal Activity Duration [hours]	Significant Wave Height Limit [Hs]	Wind Speed Limit at 10 m [Ws]	Broken/Continuous
1	0.50	6	Broken
2	1.00	8	Continuous
3	1.50	10	
4	1.75	12	
6	2.00	14	
8	3.00	16	
10	999.00	999	
12			
24			
72			
168			

For each of the parameters detailed in Table 6-3 and for each of the 24 metocean climates, multiple simulations have been run for each month of the year to capture the impact of both stochastic and systematic (i.e. seasonal / diurnal etc.) trends in the assumed climates. Several thousand simulations have been implemented for each set of variables and these have been collated as probability distributions for every combination of parameters and for each month of the year, as presented in Figure 6-2. The plots show frequency of occurrence (Y-axis) against the Actual Activity Duration (X-axis), defined here as the Ideal Activity Duration plus weather downtime.

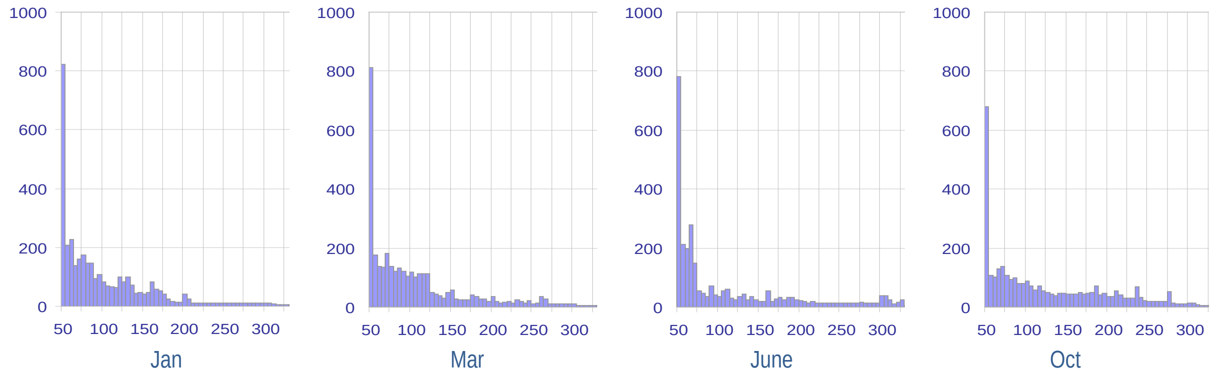


Figure 6-2: Example Monthly Activity Duration Distributions

The simulations described above were completed in-house by GL GH, resulting in 310,464 monthly activity duration distribution files, each containing probability of exceedance statistics for the Actual Activity Duration (incl. weather downtime). These files are used as inputs to Stage 2 of the modeling performed within the Installation and O&M LCoE Analysis Tool, as described in Appendix B.

6.2.3 Stage 2: Definition of Offshore Operations and Installation Sequence

Stage 2 is implemented within the Installation and O&M LCoE Analysis Tool and, as such, is subject to user inputs.

The modeling is broken down into a series of activities detailing: offshore-substation installation, wind turbine foundation installation, wind turbine installation, inter-array cable installation, and export cable installation. Each of these activities is then subdivided into a series of operations, e.g. wind turbine nacelle load-out, and each operation is further broken down into a set of sub-operations. Every sub-operation is defined by an ideal duration, significant wave height (Hs), wind speed (Ws), and whether the task can be interrupted, or be completed without interruption (broken/continuous).

The Installation and O&M LCoE Analysis Tool allows the user to either utilize default sub-operations for each activity, or, within the context of each activity, to input sub-operations with corresponding metocean limits.

The following sections define the key operations that are used to define activities within the model.

Definition of Component Load-out Operations

Load-out operations include: positioning of the vessel at the quayside, the fitting of any lifting equipment, rigging and load-out of components onto the vessel, dismantling and sea fastening of lifting equipment, and preparation and approval of the vessel for transit. The Installation and O&M LCoE Analysis Tool subdivides the process of loading-out at the marshaling port into several operations to allow the user to vary the number of components loaded out per transit to the wind farm site.

Definition of Component Transit Operations

Transit operations of components between the marshaling harbor and wind farm site include: utilization of the installation vessel, utilization of feeder barges, or float-out of components (where applicable). The Installation and O&M LCoE Analysis Tool calculates transit duration based on vessel speed and the distance between the marshaling harbor and wind farm site. Vessel speed can be informed by the user. Alternatively, the Installation and O&M LCoE Analysis Tool includes default vessel speeds. All component transits are assumed to be continuous operations which cannot be interrupted by weather delay, which is to say that transit operations require a suitable weather window.

Definition of Offshore Equipment Transfer Operations

Offshore component transfers (lifts) are generally carried out when utilizing feeder barges. For example, components are transferred at the wind farm site from the feeder barge onto the installation vessel, so that the feeder barge can then return to port to collect further components. Offshore transfers are built-up of several sub-operations encompassing: installation vessel positioning (including jacking-up if applicable), release of crane sea-fastenings, positioning of feeder barge, anchor handling tugs (AHT) laying barge anchors, and the attachment of the feeder barge to the anchor chains. Furthermore, the feeder barge is positioned against the installation vessel, the installation vessel's crane is positioned and the lifting gear attached, to allow the components to be lifted onto the installation vessel. Upon completion of the transfer, the feeder barges are disconnected from the moorings and AHTs recover the anchors.

Definition of Sea-bed Preparation Operations

Seabed preparations comprise both dredging and rock dumping. The Installation and O&M LCoE Analysis Tool assumes that the dredging vessel removes soft/uneven layers from the seabed and deposits the dredged material in an approved area within two hours' transit of the dredged area. The Installation and O&M LCoE Analysis Tool's default values assume that the dredger has the capacity to deposit material after dredging three turbine locations in series; however, this value can be altered by the user. The Installation and O&M LCoE Analysis Tool assumes that any seabed leveling will be carried out by a rock-dumping fall-pipe vessel; the model assumes that capacity of the vessel is sufficient to return to a marshaling port to collect additional rock after dumping at three turbine locations in series, though the above assumptions can be varied by the user in the Installation and O&M LCoE Analysis Tool.

Definition of Foundation Installation Operations

Jackets

The Installation and O&M LCoE Analysis Tool allows the user to select from 12 jacket installation methodologies capturing pre-piling, post-piling, driven, drive-drill-drive and drilled pin-pile installation. Jackets can be transported to the wind farm site using either installation vessels or feeder-barge transits.

Jacket foundation installation is made up two sub-operations, specifically: pin-pile installation and jacket installation. However, the sequence of operations will vary depending on the selected installation methodology.

The Installation and O&M LCoE Analysis Tool assumes that post-piled jacket installation utilizes a single jack-up installation vessel, with the jacket and pin-piles installed consecutively at each turbine location. Pre-piled jacket installation is assumed to be carried out using two separate installation vessels working in tandem to install pin-piles before installing the jackets.

Pre-piling requires a pin-pile template to aid in the installation of the pin-piles ahead of jacket installation. For instances where pre-piling is assumed, two installation methodologies have been modeled, depending on the type of transportation methodology employed.

The transportation of pin-piles using feeder-barges, allows for a solid-single deployment pin-pile template to be slung under the jack-up installation vessel (Figure 3-19). The template can be permanently slung under the installation vessel, as there is no requirement for it to transit back to the marshaling port.

Alternatively, a modular piling frame is assumed for circumstances where the installation vessel is transporting pin-piles, as the piling frame is much lighter in weight and can be supported on deck. As a result, the pin-pile jack-up vessel does not require increased draft when accessing the port.

Pre-pilled jacket installation operations include:

Pin-pile installation:

- Installation vessel positioning & jack-up / pre-load of legs;
- Release of crane-fastenings and attachment of lifting equipment;
- Lowering of pin-pile template;
- Either:
  - Transfer of piles from a feeder barge; or
  - Direct lift of pin-piles from the deck of the installation vessel;
- Driving and/or drilling of pin-piles;
- Raising of pin-pile template;
- Jack-down; and
- Installation repositioning at next turbine location (or back to marshaling port as required).

Jacket Installation:

- Installation vessel positioning & jack-up / pre-load of legs;
- Release of crane-fastenings and attachment of lifting equipment;
- Either:
  - Installation of jacket from a feeder barge; or
  - Direct lift of jacket from the deck of the installation vessel;
- Placement of jacket on pin-piles and leveling;
- Installation vessel jack-down and move to next location (or back to marshaling port as required); and
- Leveling and grouting of jacket to pin-piles (by a separate vessel spread – see below).

Post-piled jacket installation operations include:

- Installation vessel positioning & jack-up / pre-load of legs;
- Release of crane-fastenings and attachment of lifting equipment;
- Either:
  - Installation of jacket from a feeder barge, or;
  - Direct lift of jacket from the deck of the installation vessel;
- Placement of jacket on the seabed (on supporting mud-mats at each leg);
- Change of lifting equipment;
- Either:
  - Transfer of piles from a feeder barge; or
  - Direct lift of piles from the deck of the installation vessel;
- Driving and/or drilling of pin-piles through the jacket pile-sleeves;
- Installation vessel jack-down and move to next location (or back to marshaling port as required); and
- Leveling and grouting of jacket to pin-piles (by a separate vessel spread – see below).

Monopiles

The Installation and O&M LCoE Analysis Tool allows the user to select from nine monopile installation methodologies in order to cater for a range of site conditions. The Installation and O&M LCoE Analysis Tool captures: driven (just using a pile-hammer), drive-drill-drive (pile hammer and drill combined) and drilled (limited or no piling).

Monopile installation operations include:

- Installation vessel positioning & jack-up / pre-load of legs;
- Release of crane-fastenings and attachment of lifting equipment;
- Either:
  - Transfer of monopile from a feeder barge; or
  - Direct lift of monopile from the deck of the installation vessel;
- Rotation of monopole and placement in piling or drilling guide;
- Engagement of pile hammer and/or drill;
- Driving and/or drilling of pile;
- Change of lifting equipment;
- Either:
  - Transfer of transition piece from a feeder barge; or
  - Direct lift of transition piece from the deck of the installation vessel;

- Installation vessel jack-down and move to next location (or back to marshaling port as required);
- Leveling and grouting of transition piece (by a separate vessel spread – see below).

Gravity Base Structures

The Installation and O&M LCoE Analysis Tool allows the user to select from two GBS installation methodologies: GBS float-out and transport on a feeder-barge. The float-out installation methodology involves towage of the GBS to the wind farm site, followed by a controlled ballast of the foundation to the seabed. The feeder-barge methodology involves the towage of the GBS on a barge with a heavy-lift vessel on the wind farm site to lift and place the foundation on the seabed, before the addition of ballast.

GBS installation operations include:

- Installation vessel positioning & laying of anchors (feeder-barge concept only);
- Release of crane-fastenings and attachment of lifting equipment (feeder-barge concept only);
- Either:
    - Ballasting of GBS to sink it (float-out concept only); or
    - Lifting GBS off barge (feeder-barge concept only);
- Placement of GBS on the seabed;
- Ballast of GBS; and
- Feeder barge or tug returns to marshaling port as required.

GL GH has further modeled a novel GBS concept which involves the installation GBS foundation and wind turbine as a pre-assembled unit (Section 3.3.2). This concept assumes a bespoke installation vessel, which conducts a controlled lowering of the combined unit.

Floating Semi-submersible Foundation

The Installation and O&M LCoE Analysis Tool allows the user to assess a floating foundation (with pre-erected wind turbine) concept. The model assumes a float-out of the complete foundation / wind turbine unit, using seafaring tugs with anchor handling tugs providing moorings.

Semi-submersible installation operations include:

- Anchor handling tugs laying Stevmanta anchors and attaching moorings;
- Proof loading of moorings;
- ‘Hand-over’ of the foundation from the primary transit tug to anchor handling tug;
- Connection of the foundation to moorings; and
- Tensioning of moorings; and
- Vessels return to marshaling port as required.

Definition of Foundation Grouting Operations

The Installation and O&M LCoE Analysis Tool assumes that any grouting operations, where required, encompass:

- Positioning of the grout vessel;
- Preparation of grout equipment and connection of all grout hoses;
- Leveling of components (transition pieces, jackets, etc.);
- Mixing and pumping of grout into annulus;
- Partial grout curing; and
- Grout vessel moves to next location (or back to marshaling port as required).

The Installation and O&M LCoE Analysis Tool assumes that the grout vessel continues onto the next foundation location after grouting completion with a partial curing of the grout. Further to this, it is assumed that grouting can commence once a certain fixed number of foundations have be installed, with foundation installation and grouting continuing in parallel.

Definition of Foundation Scour-protection Operations

The Installation and O&M LCoE Analysis Tool assumes that any rock-dumping operations, where required, encompass:

- Positioning of the rock-dump vessel;
- Transfer of rock material to conveyer system;
- Rock-dumping;
- Repositioning and repeat of the above; and
- Rock-dump vessel moves to next location (or back to marshaling port as required).

The Installation and O&M LCoE Analysis Tool assumes that a conveyer rock-dump vessel is used to install scour protection around the base of monopile and GBS foundations, since (i) it is considered unlikely that a fall-pipe could be maneuvered close enough to the foundation and (ii) space-frame foundations (e.g. jackets) are typically less affected by scour.

Definition of Electrical Balance of Plant Installation Operations

Offshore Sub-station

The Installation and O&M LCoE Analysis Tool assumes a post-piled jacket foundation installation methodology for the offshore sub-station. This is the usual approach in Northern Europe, given that a pre-piled installation methodology would require a bespoke (single use) piling template due to the fact that the sub-station jacket is assumed to be significantly larger than wind turbine foundation jackets.

The Installation and O&M LCoE Analysis Tool assumes that a large jack-up installation vessel would not have adequate deck space to directly install the large jacket foundation/topside. It is therefore assumed that the installation of the jacket foundation and sub-station topside is carried out by a heavy lift vessel lifting the foundation off a feeder barge. Attachment of the topside to the foundation is also included in the above set of operations.

Sub-sea Cabling

Two subsea cable installation methodologies have been captured within the Installation and O&M LCoE Analysis Tool. The first assumes the plowing of cables into the seabed (Figure 3-30), while the second involves the jetting of cable into the seabed. For inter-array and export cabling the following operations have been assumed:

Export cabling (per length):

- Positioning of cable lay vessel at the shore;
- ‘Float-in’ of cable end to the export cable transition pit;
- Set-up of cable plow in the tidal-zone;
- Initial pull-in of cable plow with installation of cable in tidal-zone;
- Floating of the vessel (awaiting tide);
- Cable burial to the offshore sub-station;
- Pull-in of cable at the offshore sub-station;
- Jetting and burial of the cable-end at the base of the J-tube;
- Seabed survey of cable route; and
- Cable testing.

Inter-array cabling (per length):

- Positioning of cable lay vessel at Wind Turbine #1;
- Pull-in of cable at Wind Turbine #1;
- Deployment of jetting spread;
- Cable burial to Wind Turbine #2;
- Pull-in of cable at Wind Turbine #2;
- Seabed survey of cable route;
- Cable testing; and
- Installation by rock-dump vessel of protection over cable-ends at J-tubes.

Definition of Wind Turbine Installation Operations

The Installation and O&M LCoE Analysis Tool allows the user to select from three wind turbine installation methodologies including: single-blade, single-rotor, and complete wind turbine installation. These three methodologies are intended to capture current and emerging practices. In all cases it is assumed that wind turbines are transported to the wind farm site using the installation vessel.

Wind turbine installation operations for single-blade and full-rotor include:

- Installation vessel positioning at foundation;
- Jack-up of installation vessel and pre-load of legs;
- Release of crane-fastenings and attachment of lifting equipment;
- Either:
    - Single Blade:
        - Lift and erection (bolting) of the wind turbine tower (two separate lift sections);
        - Lift and erection of the nacelle; and
        - Lift and erection of individual blades (three separate lifts);
    - Complete Rotor:
        - Lift and erection (bolting) of the wind turbine tower (two separate lift sections);
        - Lift and erection of the nacelle; and
        - Lift and erection of the complete rotor-star (single lift); and
- Installation vessel jack-down and move to next location (or back to marshaling port as required).

In the case of a complete wind turbine lift, offshore operations include:

- Installation vessel transits to the wind farm site with the pre-erected wind turbine;
- Lift of the wind turbine and positioning above the foundation;
- Lowering to interface connection;
- Bolting of the wind turbine to the foundation; and
- Installation vessel transits back to marshaling port.

6.2.4 Stage 3: Definition of Installation Constraints

GL GH has provided baseline vessel and plant requirements for each of the activities defined in Stage 2. Given the early stage of the offshore wind market in the U.S., there may be a lack of appropriate installation vessels available to offshore wind farm developers. This may require such vessels to be either commissioned within the U.S. or sourced from pre-existing stock in Europe. Were an offshore wind farm developer to opt for the latter approach, the installation vessel would have to mobilize offshore on the wind farm site, with foundations, wind turbines, etc. being transported to the vessel using feeder vessels. Given the above considerations, GL GH has supplied baseline vessels which are comparable to those available in Northern Europe.

Table 6-4 presents the default installation and support vessel capabilities and operational limiting states in the Installation and O&M LCoE Analysis Tool for the installation methodologies described in Stage 2. Also included within this table are the assumed vessel characteristics as well as their assumed transit metocean limits. Note that these transit metocean limits apply only to transit and therefore differ from operation-specific limitations.

It should be noted that while the foundation, balance of plant and turbine installation operations for Stage 2 (as outlined in Section 6.2.3) reflect the manner in which the model has been configured by default, the user does have some freedom to vary these assumptions within the Installation and O&M LCoE Analysis Tool through the alteration of durations, weather constraints, and vessel capacities. For example, if jackets are proposed to be installed from a floating vessel, then the time spent jacking up and jacking down can be re-specified to accommodate vessel positioning and anchor handling. Likewise, the significant wave height limits imposed on some of the operations can be altered to reflect the greater sensitivities associated with a floating vessel spread. Finally the number of jackets per trip from port could be re-defined according to the specifications of the proposed vessel.

Table 6-4: Vessel and Plant Assumptions within the Installation and O&M LCoE Analysis Tool

Vessel/Plant	GL GH Assumptions	Vessel Speed Unloade[1] [knots]	Vessel Speed Loaded[1] [knots]	Hs[1]	Ws[1]	Applicable Installation Methodologies
Dredger	Certain soil conditions around the U.S. coast may require the use of a dredger in order to level the seabed to install foundations. A dredger can also be utilized for the removal of low strength seabed strata in order to reveal sufficiently hard ground conditions beneath. The model assumes that the dredger transits to an approved area for discharging deposited materials every third wind turbine location; however, this value can be altered by the user if desired.	8	8	1.6	10.7	GBS Post-piled jackets
Large Jack-Up Vessel	The Installation and O&M LCoE Analysis Tool assumes a new generation dynamic positioning (DP2) jack-up installation vessel, based on a generic specification widely available among this fleet of Northern Europe new-build vessels. It is assumed that the vessel can jack-up on legs to provide stability at the necessary crane heights. The Installation and O&M LCoE Analysis Tool assumes a deck capacity which can store three sets of jacket pin-piles and three jackets; however, vessel storage capabilities and costs can be varied by the user.	8	8	2.2	13.8	Turbines Jackets Monopiles
Small Towed Jack-Up Vessel	Utilized when a high level of stability is required without the need for high lift capacity or cargo carrying capacity. The vessel has no on-board propulsion system and is therefore towed by tugs.	6	6	2.2	13.8	Pre-piling
Rock Dump Vessel	Rock-dump vessels are assumed to have the capability to discharge rock from the side in order to provide scour protection. These vessels are fitted with dynamic positioning systems and hopper tipping mechanisms to accurately control deposition; high maintenance is therefore required, resulting in expensive day rates.	8	8	2.2	13.8	Monopiles GBS
Grout Vessel	The Installation and O&M LCoE Analysis Tool assumes a separate grout vessel is utilized in order improve installation cycles by allowing the installation vessel to progress to the next wind turbine location. In general, grouting involves the mixing of specialist cement and aggregate material, followed by pumping it through flexible hoses into a prepared cavity (annulus). Additional duties include monitoring that all voids are filled and that spillage of this potentially toxic material is avoided and any spills are safely contained. Relatively lightweight floating vessels can successfully fulfill this role. The Installation and O&M LCoE Analysis Tool assumes that hydraulic jacks are utilized when leveling	10	10	2.2	13.8	Monopiles Jackets

Vessel/Plant	GL GH Assumptions	Vessel Speed Unloade^1 [knots]	Vessel Speed Loaded^1 [knots]	Hs^1	Ws^1	Applicable Installation Methodologies
	foundations or transition pieces, in preparation for grouting.					
Bollard Tug	Tugs have been utilized wherever towage of feeder-barges, small jack-up vessels, towage of monopiles, towage of GBS foundations, and towage of floating foundations with pre-assembled turbines have been assumed. The Installation and O&M LCoE Analysis Tool assumes that two tugs (40 – 80 tons bollard pull) are required to tow and maneuver each barge.	6	6	2.2	13.8	Deck Barges Towed Jack-Up Towed-foundations Floating-foundations
Feeder-Barge	Certain installation strategies involve feeder-barges as a cost-effective solution to transport components to the wind farm site, allowing the installation vessel to remain on site. The model assumes barge dimensions of 300’ x 90’ (approximately 91 m x 27 m). The Installation and O&M LCoE Analysis Tool assumes a deck capacity which can carry up to three jacket foundations in any one transit.	6	6	2.2	13.8	Monopiles Substation Pre-piled Jackets
Anchor Handling Tug (AHT)	It is assumed that it is quicker and more cost effective to lay anchors using AHTs when utilizing installation vessels and feeder-barges without DP capabilities (thereby requiring anchors for vessel positioning). AHTs are large with considerable bollard pull capabilities, often well in excess of 100 tons and have large aft deck areas to allow the carriage of several anchors and large quantities of anchor cable.	6	6	2.2	13.8	Deck Barges Towed Jack-Up Heavy Lift Vessel
Crawler Crane	Land-based cranes are generally used on the port quayside to assist with the load-out of certain components. Crawler cranes are mobile units and therefore very useful for the movement and loading of wind turbine components and foundations.	-	-	-	-	Monopiles Sub-station jackets
Ancillary Equipment	It is assumed that drilling spreads are required for drilling activities. Drill spreads comprise rotary equipment but not the drill bits. Rock drilling is likely to be required at certain sites in order to provide a hole in the bedrock into which a monopile / pin-pile may be inserted and grouted. The Installation and O&M LCoE Analysis Tool assumes a large diameter rotary drill bit and a mid-range drill progression rate; however, this can be altered by the user in order to comply with the varied site conditions around the U.S. Coast. The Installation and O&M LCoE Analysis Tool assumes that the drilling spread is made up of two drills. Further to the drill spread, the Installation and O&M LCoE Analysis Tool assumes two alternative piling spreads; a vibro-hammer spread and an impact hammer spread,	-	-	-	-	Monopiles Jackets

Vessel/Plant	GL GH Assumptions	Vessel Speed Unloade[1] [knots]	Vessel Speed Loaded[1] [knots]	Hs[1]	Ws[1]	Applicable Installation Methodologies
	for driven or drilled monopiles / pin-piles, respectively. The Installation and O&M LCoE Analysis Tool also captures the requirement for lifting spreads to be utilized during component load-outs, transfers, and installation operations.					
Workboat	Some installation methodologies assume workboat vessels, essentially lightweight crew transport vessels with fairly high transit speeds of approximately 20knots. Workboats are utilized to transport technicians to the wind farm site, where they are transferred onto wind turbines or the offshore substation to complete jobs such as commissioning, welding, etc.	20	20	1.5	10	Substation Export Cables Array Cables Commissioning
Heavy Lift Vessel	Heavy lift vessels are required when components outweigh the capabilities of standard jack-up or floating cranes (usually in the range of 400-600 tons). The vessel is usually a large floating platform (such as a sheerleg), and is assumed to be positioned on site using an anchor spread. Feeder-barges are used to transport equipment and are transferred to the heavy-lift vessel by mooring alongside.	6	6	2	14	Substation-foundation Substation-topside
Special Purpose Multi-wheeled Transports (SPMT)	SPMTs are used in situations where large pieces of equipment (GBS, sub-station topsides, etc.) need to be transported between manufacturing areas and the port quayside. They are generally used for large components that cannot easily be transported by crawler cranes.	-	-	-	-	Sub-station topsides GBS

1. Indicates GL GH's default values; however, these can be varied by the user if necessary.

6.2.5 Stage 4: Definition of Installation Sequence

Having defined all activities at operation and sub-operation levels, and having defined operating limitations for all sub-operations, the broad installation program is defined in the model by assigning inter-dependencies between activities.

Figure 6-3 presents the overall installation program captured within the Installation and O&M LCoE Analysis Tool. Dependencies between each activity are shown as arrows, with start date of some activities influenced by the finish date of proceeding activities. It is therefore possible that an activity's true start date can be later than the user's specified mobilization date for that activity.

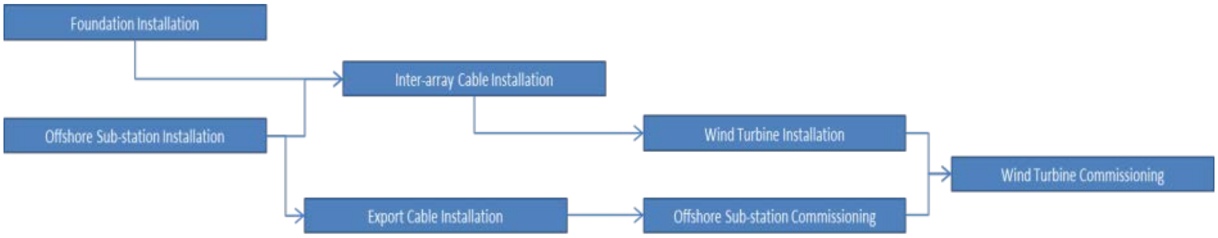


Figure 6-3: Installation Program Defined within the Installation and O&M LCoE Analysis Tool

The installation program within the Installation and O&M LCoE Analysis Tool assumes that a wind turbine 'string' (where a 'string' is defined as a single electrical circuit connecting the wind turbines to the offshore sub-station) consists of six locations. It is inherent in the installation program that once a 'string' of foundations is installed, it is possible to begin installation of inter-array cables for that 'string'. The same is true of the dependency between inter-array cable and wind turbine installation.

In situations where a user specifies an installation activity start date (where start date is defined by the latest mobilization date for vessels or plant required for that activity) that is earlier than the actual start date (driven by the finish date of the preceding activity), the Installation and O&M LCoE Analysis Tool identifies the duration for which the vessels and plant are idle as 'Logistic Delay' (Figure 6-4).

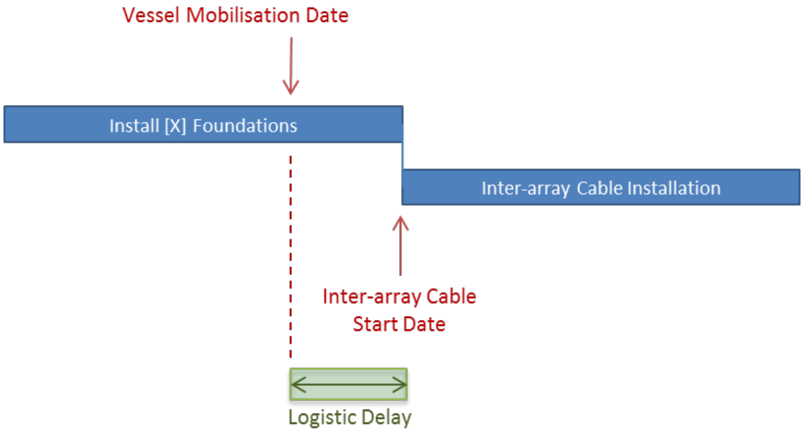


Figure 6-4: Definition of Logistic Delay

For the opposite scenario, where the mobilization date is later than the actual, or potential, start date, the Installation and O&M LCoE Analysis Tool captures this opportunity duration as 'Vessel Delay' (Figure 6-5).

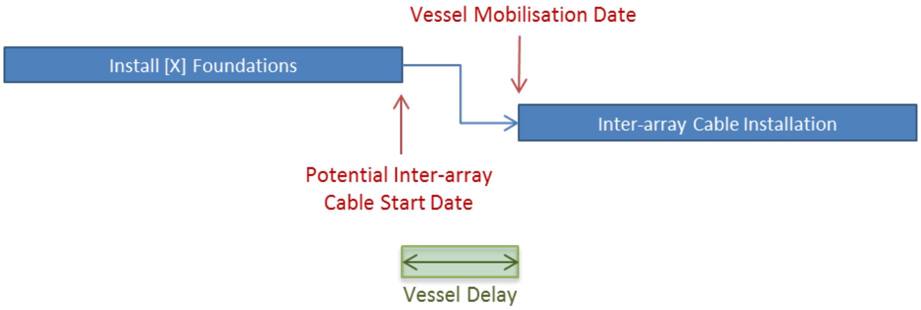


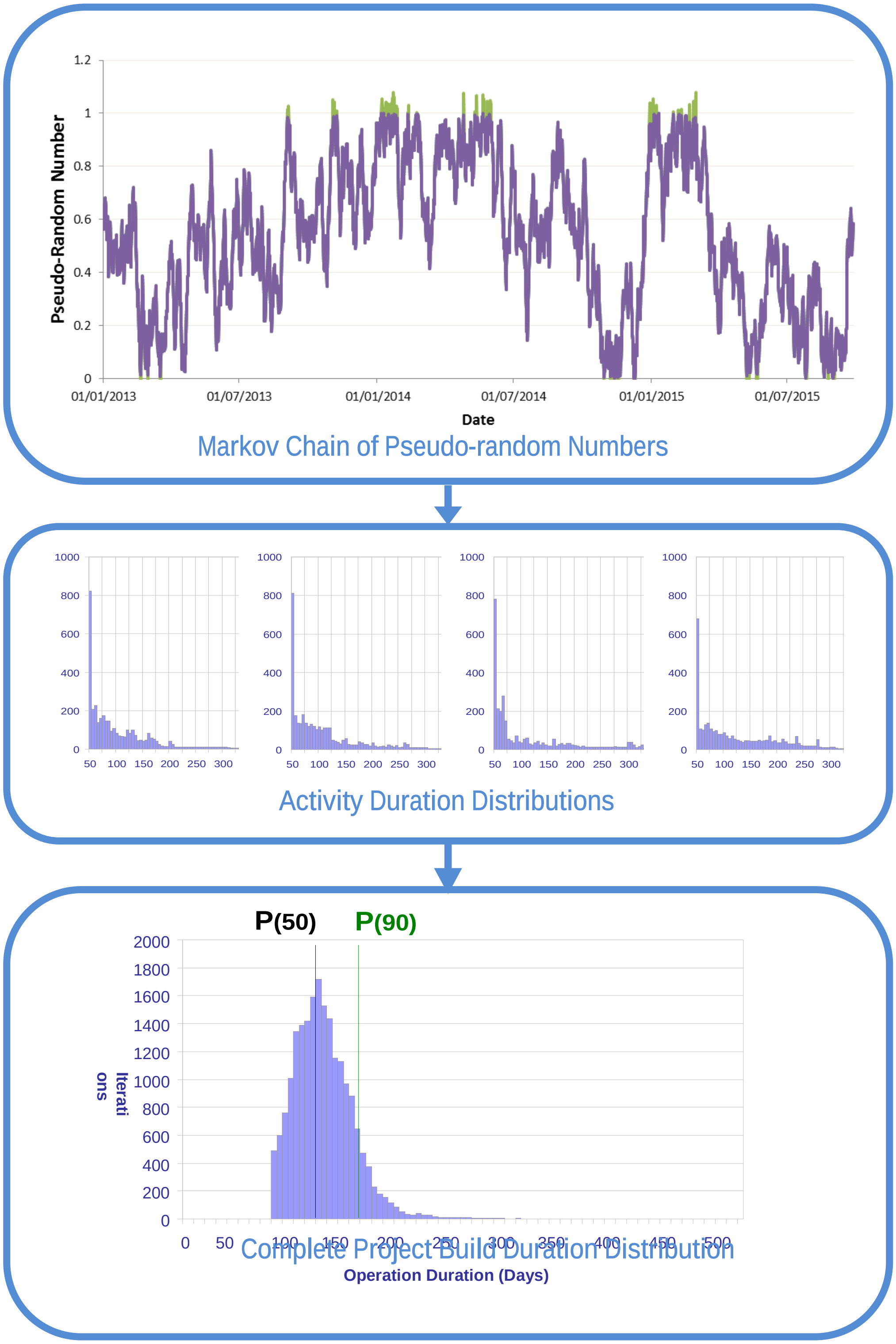
Figure 6-5: Definition of Vessel Delay

Durations for each installation activity are derived by determining the relevant activities' vessel/plant mobilization dates and resultant finish date (taking all weather and logistic delay into consideration). The determination of stochastic weather downtime is further described in Stage 5. The resultant activity durations are taken forward in conjunction with vessel/plant day rates, discussed further in Stage 6.

The sequencing of activities, operations and sub-operations (Stage 4) may not be varied within the Installation and O&M LCoE Analysis Tool.

6.2.6 Stage 5: Monte Carlo Analysis

The probabilistic activity durations described in Stage 1 (Figure 6-2), which capture generic durations (including weather downtime) for specified operating weather windows, are combined with the installation methodologies and their required operational windows (Stage 2), the operating limitations and vessel characteristics (Stage 3) and the installation project program (Stage 4) using a Monte Carlo Engine (MCE). The MCE runs multiple iterations, using a Markov Chain of calibrated pseudo-random numbers. These random numbers sample the probabilistic activity durations generated in Stage 1, based on the required operating weather windows and their metocean limiting requirements defined in Stages 2 & 3 and the month of the year derived using the sequencing defined in Stage 4, to derive overall activity duration distributions. The subsequent activity duration distributions are combined, as part of the project program, to derive the complete project build-out duration distribution. The process is described in Figure 6-6.


1.2
1
0.8
0.6
0.4
0.2
0
Pseudo-Random Number
01/01/2013
01/07/2013
01/01/2014
01/07/2014
01/01/2015
01/07/2015
Date
Markov Chain of Pseudo-random Numbers
1000
800
600
400
200
0
50 100 150 200 250 300
Activity Duration Distributions
P(50)
P(90)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Iterations
0 50 100 150 200 250 300 350 400 450 500
Operation Duration (Days)
Complete Project Build Duration Distribution

6.2.7 Stage 6: Installation Vessel & Ancillary Equipment Cost Assumptions

Durations for each activity, such as wind turbine installation, are combined with appropriate installation vessel and plant day rates and mobilization costs to derive an overall installation cost.

GL GH has provided baseline vessel and plant day rates and mobilization costs within the Installation and O&M LCoE Analysis Tool. Given the early conception of the offshore wind market in the U.S., much of the vessel and plant requirements may not available and may have to be commissioned or sourced from Europe. Were an offshore wind farm developer to opt for the latter approach, the installation vessel would have to mobilize offshore on the wind farm site, with foundations, wind turbines, etc. being transported to the vessel using feeder vessels. Given the above considerations, GL GH has supplied baseline vessel costs which are comparable to current Northern European figures, factored to U.S. dollars.

The vessel day rate represents the cost of utilizing the vessel for a 24-hour period regardless of whether it is performing work or waiting on weather. A mobilization rate has also been estimated; this value includes the transit of the vessel to the mobilization port and any necessary retrofitting of the vessel. GL GH has assumed that all vessels can be mobilized in five days, although these unit cost assumptions can be varied by the user within the Installation and O&M LCoE Analysis Tool if required.

Table 6-5 and Table 6-6 present vessel and plant cost assumptions. These day-rate and mobilization costs are default values within the Installation and O&M LCoE Analysis Tool, although the user has the capability to amend these costs.

Table 6-5: Vessel Cost Assumptions

Vessel Details	Day Rate [$]	Mobilization Cost [$]
Crawler Crane	5000	50000
Large Crawler Crane	8000	80000
Self-Propelled Modular Transports (SPMT)	4,000	8,000
Substation Transportation Barge	35,0000	175,000
Substation Heavy Lift Vessel	500,000	2,500,000
Substation Welding Workboat	8,000	16,000
Commissioning Vessel	8,000	16,000
DP2 Jack-up Vessel	250,000	1,255,000
Grout Vessel + Spread	50,000	250,000
Feeder Barge	20,000	100,000
40-80T Bollard Tug	17,500	35,000
Anchor Handling Tug	37,500	75,000
Dredger	100,000	500,000
Fall-pipe Vessel	85,000	425,000
Towed Installation Jack-up Vessel	135,000	675,000
Specialized Heavy Lift Vessel	500,000	2,500,000
Crane Barge	300,000	1,500,000
Array Cable Installation Vessel	75,000	375,000
Array Cable Termination Vessel	8,000	16,000
Array Cable Testing Vessel	8,000	16,000
Export Cable Laying Vessel	130,000	650,000
Export Cable Survey Vessel	25,000	125,000
Export Cable Testing Vessel	8,000	16,000

Table 6-6: Ancillary Cost Assumptions

Vessel Details	Day Rate [$]	Mobilization Cost [$]
Piling Spread (Impact Hammer)	20,000	100,000
Piling Spread (Vibro Hammer)	10,000	50,000
Lifting Spread	50,000	250,000
Drilling Spread	20,000	100,000
Ballast Spread	500	2,500
Port Costs	-	14,000,000
Pre-Installation Logistics (Transport)	-	24,300,000
Onshore Equipment Costs	-	2,600,000

The resultant Installation CapEx is derived through the product of the activity durations (including weather downtime and logistic delay) and the vessel/plant day rates, summed with the costs associated with the mobilization of vessel and plant. Further cost items are included within the Installation and O&M LCoE Analysis Tool, to take account of the bespoke requirements for certain foundation concepts. For example, there are significant costs associated with the need for space for GBS fabrication, with fabrications times potentially taking as long as 90 days per GBS foundation.

7 OPERATIONS AND MAINTENANCE MODELING ASSUMPTIONS

7.1 Modeling Approach

After reviewing current access methodologies, recent technology developments and future trends as described in Section 4 and considering U.S. specific site conditions and the potential development of the U.S. marine market to service offshore wind farms within its coastal regions, GL GH has considered the following access methodologies for the simulation of O&M logistics and cost estimation of a generic 504 MW offshore wind farm:

1 Port-based work boats

As described in Section 4.2, this is the most common access methodology in current operational wind farms and consists of work boats based at an onshore port which transfer technicians to the offshore structures. There are no apparent barriers for the acquisition of workboats from the current European market, nor for their potential construction within the U.S. and therefore this strategy has been simulated to estimate resources and costs involved and to provide a useful benchmark representing current practice. Given the wide variety of work boat designs currently available and considering future trends and improvements, GL GH has provided flexibility within the model in order to capture the anticipated capabilities of the designs described in Section 4.2.3 (e.g. quick response vessels, traditional catamarans, and SWATH vessels). The selection of a specific vessel is made by varying the significant wave height limit, speed, fuel consumption, and annual cost of the vessels as further described in Section 4.

2 Port-based work boats plus helicopter

Given the onerous metocean conditions at many development sites, the utilization of helicopters could significantly improve the performance of an offshore wind farm located in U.S. waters. With no apparent overarching barriers for the use of helicopters to transport crews between an O&M service base and an offshore site, GL GH has considered it as a potential option for modeling purposes. More details on this strategy are given in Section 4.

3 Mothership with Daughter Crafts

For far-shore sites a mothership equipped with daughter crafts offer a potential access strategy. Similarly to work boats and helicopters, there are no apparent barriers for such vessels to be sourced from the European market or from local vessel suppliers. Due to the wide variety of daughter crafts which could be used in conjunction with a mothership, GL GH has enabled the model to assess different types of daughter crafts through the modeling of a range of alternative Hs limit capabilities. For more details on this strategy, see Section 4.

4 Offshore based personnel with work boats

As stated in Section 4.2.5, the use of an offshore fixed platform as an O&M base could represent a potential option for far-shore sites in the U.S. Under this approach, work boats are assumed to be used to transport technicians the short distances between the offshore platform and the turbines. For more details on this strategy, refer to Section 4.

5 Jack-up vessel as an accommodation platform

Similar to the previous strategy, this strategy utilizes a jack-up vessel to act as an offshore O&M base. This vessel has the additional benefit of having the capacity for replacing major components in the wind farm and of being able to relocate if necessary. Despite the high capital costs involved in this strategy, there are no current barriers for such a vessel to be procured and used within the U.S. It must be noted that for the Great Lakes region, there are only a few vessels available in the current market which could access the Lakes through the Great Lakes St. Lawrence Seaway System and their conversion into accommodation platforms would be required.

6 Port-based work boats plus hovercraft (for Great Lakes Region only)

Because of accessibility limitations caused by sea ice in the Great Lakes region, GL GH has considered it practical to assess the use of alternative transportation systems such as a hovercraft to support the O&M activities when work boats cannot access the turbines. More details on this strategy are found in Section 4.

7 Other emerging vessels and transfer solutions

As described in Section 4.2.6, the offshore wind energy industry is under fast development and since accessibility to the turbines has been the main challenge faced by the industry, new vessel designs and access systems are being developed and tested at certain operational wind farms. The consideration of future technology development is of vital importance for the analysis of a potential deployment of offshore wind farms within the U.S.; for these reasons, GL GH has provided flexibility to the cost of energy model and has enabled the user of the Installation and O&M LCoE Analysis Tool to vary the capabilities of work boats, daughter crafts and the use of different access systems.

7.2 The O2M Model

In order to provide estimates of wind farm availability and operational costs for an offshore wind project, it is necessary to make a number of assumptions relating to the O&M infrastructure serving the project in question, the costs associated with the component elements of that infrastructure and the modeling approach adopted. The assumptions made for the analysis described in this Report are described in this section.

The results of the O&M Analysis of this study are based on computer modeling using the in-house GL GH simulation tool, O2M Plus ("Optimization of Operation and Maintenance"). Principally, the O2M Plus Model is used to predict wind farm availability and the associated cost of O&M activity.

The model is run forward in the time domain, the overall approach being based on a Monte Carlo simulation, with turbine failures occurring on a stochastic basis. Delays associated with poor weather are simulated using long-term metocean data for the site of interest. Figure 7-1 shows a simplified block diagram of the O2M Plus Model; a more detailed description of the model structure follows.

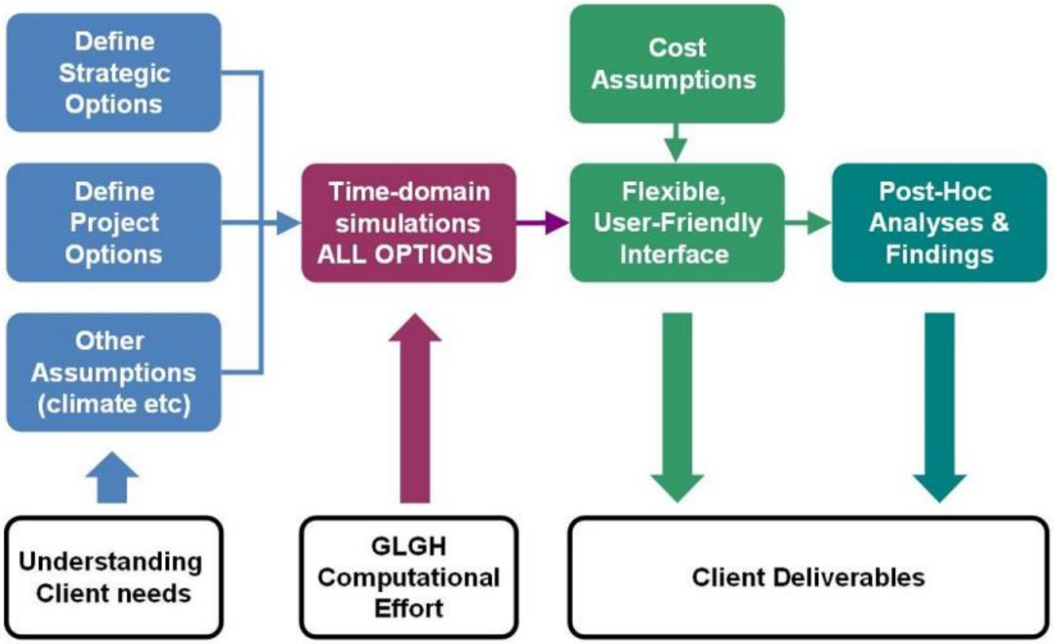


Figure 7-1: Simplified Block Diagram of the O2M Plus Model

The main environmental input dataset comprises a time series of significant wave height (Hs) and concurrent wind speed, derived as described in Section 5. The relationship between Hs and wind speed is therefore intrinsically captured enabling the modeling to simulate the effect of poor wind farm accessibility during periods of high wind and hence high production potential.

The wind farm project itself must also be described. The number of turbines, store location, service base location, mobilization times, and travel times are defined as input data to the O2M Plus Model. Also required is a prediction of the idealized long-term net energy output of the wind farm, neglecting availability losses and broken down by month. This seasonal breakdown is required in order to model the "high wind – low access" effect described above.

The O&M resources available to the wind farm comprise the service crews, access vessels, specialist vessels, and spares holding facilities. Staffing inputs include the number of crews, their associated cost, shift rota, and working days per week. In addition to the transit speed, the turbine primary access method is defined by a limiting Hs and wind speed level for safe turbine access. Spare parts are associated with turbine failure modes and each part has a cost, nominal spares holding level, and re-order lead time.

A schedule of turbine failure modes is required as a model input. This schedule is of critical importance to the model operation and output since it comprises the turbine reliability projection and maintenance requirements. The failure mode schedule includes as many modes of failure as is felt appropriate for the turbine model under consideration. For each mode, the following criteria are defined: Mean Time Between Failures (MTBF), Direct Time To Repair (DTTR), spare part type required, and whether the repair requires a specialist crane vessel such as a jack-up barge. In addition, the scheduled maintenance requirements of the turbines under consideration form an important input. The minimum and maximum service interval and the duration of each service in crew-hours are defined.

Inherent assumptions in the O2M Model govern the status and behavior of all system elements: turbines, crews, parts and spares. Some important examples of these include:

- Crews may not be deployed unless a suitable vehicle is available.
- A suitable vehicle is one with sufficient spare passenger capacity, parts carrying capacity and which has wind speed, sea-state and tidal limitations in excess of current conditions.
- Repairs and scheduled maintenance activities are interrupted by worsening weather conditions.
- Faults are not diagnosed until a crew has visited the turbine in question.
- Upon diagnosis, if a spare part is required for the repair, the attending crew must travel to the parts store to pick up the part in question (if available) and before returning to the turbine to begin the repair operation.[1]
- Should the diagnosed fault category require a spare part beyond the capabilities of the access method used for the initial visit, the attending crew will change vessel once back at the parts store should an appropriate vessel be available. The turbine in question will remain inoperative through diagnosis and logistics until the repair operation is complete.
- Repairs can only commence if the appropriate spare part is available and has been retrieved from the parts store.
- If a repair is not finished by the end of a crew's shift, the job will be continued when the next crew comes on shift, if they are available and access is possible. The turbine in question will remain inoperative until the repair operation has been completed.
- As soon as a spare part is taken from the store, a replacement is ordered.
- After completing a repair, crews will return to base unless there is another repair to attend or scheduled maintenance is due.
- Crews are only dispatched if they can complete the journey to the wind farm and complete at least 1 hour’s work within their current shift.
- Crews return to port (or offshore base) by the end of their shift.

Availability and other wind farm operational parameters can be calculated in the frequency domain through the combination of probability distributions for various situations. However, in practice, such calculations become unmanageable for all but the simplest cases. In order to overcome this limitation, a time domain Monte Carlo approach has been adopted, which relies on random number generation to ensure that all possibilities are covered in an unbiased manner. Such an approach requires both deterministic and stochastic events. While the former is governed by the inputs and assumptions outlined above, turbine failures and weather conditions comprise the stochastic and quasi-stochastic elements of the simulation.

During a simulation, each operational turbine is given the opportunity to fail at each time step, which is nominally 1 hour. At this point, the model cycles through the failure mode schedule in a randomized order. For each failure mode a random number, R, between 0 and 1 is generated from a uniform distribution and compared to the MTBF (in hours), for the failure mode in question. If the condition set out in Expression (1) below is satisfied, then the turbine in question is said to have failed in the current time step, in the failure mode under test.

$$R < 1 - e^{-1/MTBF} \qquad (1)$$

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[1] Diagnosis and part retrieval logic applied for all access methods including for helicopter operation.

When a failure occurs, the turbine is shut down and a crew, if available, is allocated to perform the repair. If all crews are either occupied with repair operations or are not on duty, the turbine will remain down, and a crew will not be assigned until one becomes available for work.

When a crew becomes available and is assigned to conduct the repair work, that crew can only be deployed to the failed turbine if the current weather conditions (Hs and wind speed) are within the turbine access limits as defined in the model inputs for any available and suitable vessel. If these conditions are not met, the crew remains at its base and is only dispatched to the assigned turbine once the weather improves to within the access limits. Given favorable weather conditions, the crew will be dispatched to its assigned turbine.

The time taken to repair the turbine once the crew is in attendance is determined by the DTTR value specified for the fault in question. The model keeps track of the repair time remaining as the repair work progresses. Once the repair work is complete, the turbine is restarted and the crew either returns to base or goes on to any other turbine in the wind farm requiring repair or maintenance.

If, during repair, weather conditions worsen to a level beyond the turbine access limits specified, repair operations are suspended and the crews return to base if an appropriate vessel is available. In this instance, the turbine concerned remains inoperative. However, the work already completed is logged so that the job can be continued when the turbine is next accessed.

Scheduled maintenance or servicing is implemented by the crews within the specified service interval, where possible. It is assumed that turbines can be restarted when scheduled servicing work is interrupted, with the service being completed when another crew becomes free and can access the turbine. Scheduled maintenance operations are also subject to weather delays in the same manner as those associated with repair work, albeit with the important difference that no turbine downtime is accrued while waiting on weather for scheduled works.

Clearly, there is scope for a wind farm O&M simulation in which crews cannot keep up with the specified scheduled maintenance requirements. In these cases, the assumption of a constant MTBF value for turbine faults throughout the simulation becomes unrealistic, invalidating the model outputs, i.e. Turbines will fail more frequently if they are not serviced frequently enough. The model identifies whether the maximum specified service interval has been exceeded for any of the turbines throughout the simulation and a view can then be taken on the validity of the model outputs for the simulation, given the frequency and severity of this exceedance. An acceptable average achieved maintenance interval of the planned maintenance interval +10% is defined and if any simulation falls outside of this, the results are rejected and the simulation re-run with increased scheduled maintenance resource.

The duration of the wind farm simulation is defined as an input. Given the stochastic nature of the model, it is preferable to initiate a long simulation to ensure that the outputs of interest are highly converged. The duration required to reach an acceptable level of convergence will vary depending on input assumptions, but for most scenarios, a simulation of 100 years has been found to be sufficient. During the simulation, the O2M Model records the status of each element of the wind farm at every time step. In addition, key output variables of interest are recorded throughout the simulation, such as availability and lost production. The resulting database has been used to create the O&M Analysis section of the Installation and O&M LCoE Analysis Tool.

7.2.1 Dimensions Considered

It is important to note the difference between the maximization of wind farm availability and the optimization of O&M strategies. Given that wind turbines are imperfect and will fail, 100% availability will (in theory) be achieved at an O&M cost tending to infinity. At the other end of the scale, with zero investment in O&M, the long-term availability of the wind farm will be close to zero. In general terms, the situation is summarized graphically in Figure 7-2.

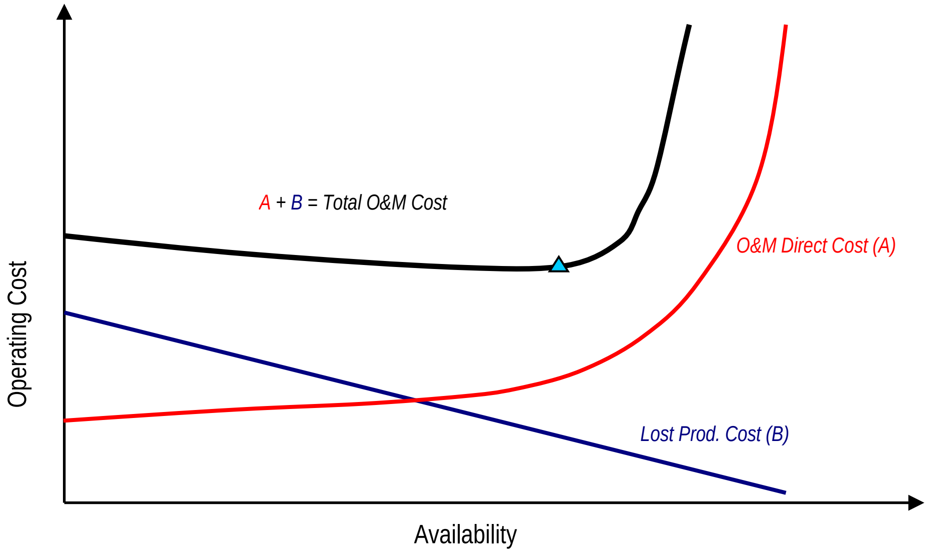

Figure 7-2: Indicative Variation in Direct, Lost Production and Total Costs with Availability

In addition to the direct costs associated with O&M resources (red line), the other major cost component of wind farm operation is that associated with lost revenues due to turbine downtime (blue line). The sum of these two cost sources (black line) provides the total cost of O&M. The indicative trends assumed in this figure for the two cost components yields a minimum total cost, denoted by the blue triangle. This point is associated with the optimum O&M strategy for the wind farm and the most economic long-term availability level.

The O2M Model can be used to estimate where the O&M cost optimum lies for a given set of input assumptions. This is achieved through multiple simulations with alternative input parameters in each case. In practice this is undertaken by first identifying any project options which are not yet fully defined or which comprise key areas of uncertainty. Project options are those parameters which are assumed to be fixed once the project has been built, but will have an impact on the O&M resources required, such as turbine reliability, distance from base or the number of turbines in the project.

Once the project options have been defined, optimal strategic options may be identified by seeking the minimum total O&M costs as defined above. Strategic options are defined here as those parameters associated with O&M resource and logistics and will hence affect both O&M costs and the resulting availability.

These options, be they related to O&M strategy or project configuration, are characterized in the study and reported here as 'dimensions'. To capture the combined impact of these dimensions and their various inter-dependencies, a single simulation has been conducted for each possible combination of the defined dimensions. For example, if three dimensions are defined, each with two possible options, 8 independent simulations would be implemented (2x2x2). A description of the dimensions and their associated options is provided in the following sub-section.

Non-Optimized Dimensions

Seven dimensions have been defined for the project which constitute project configuration or scenario options and are thereby considered to **not** be the subject of optimization. These are described below.

U.S. Coastal Regions

The influence of metocean climates on Operation and Maintenance activities, and its variability across the U.S. Coasts will be captured as part of the background modeling undertaken. The model considers the eight discrete coastal regions defined in Section 2.

Metocean Climates

Metocean conditions vary considerably within each of the defined regions. In order to capture this variability across each region, GL GH has used the 24 metocean climates (3 per region), each defined by 33 years of wind speed and significant wave height data time series compiled as described in Section 5. Table 5-1 shows the long-term mean significant wave height and wind speed of each of these metocean climates.

Project Configuration

Considering current market technology and future market trends, GL GH has modeled two alternative project configurations for wind farms within the U.S., as presented in Table 7-1. It is important to note that no distinction has been made between the reliability assumptions adopted for each turbine model considered within this analysis.

Table 7-1: Project Configuration Options

Option	WTG Model	Number of WTGs	Total Site Capacity [MW]
1	Generic 4 MW	126	504
2	Generic 6 MW	84	504

WTG Reliability

Assumptions on wind turbine reliability will have a large impact on estimates for the long-term availability and O&M costs associated with any wind farm. A study has been conducted by GL GH based on in-house experience and knowledge, academic studies and published case studies to derive typical failure rates, repair durations and spare / equipment requirements for four broad classes of turbine failure. Published case study data from Tuno Knob (DK), Altamont Pass (U.S.), Nysted (DK) and Big Spring (U.S.) wind farms, alongside GL GH operational experience analyzing proprietary data, were given a higher weighting in the reliability profile derivation than results from published academic studies, which were generally considered to be significant overestimates of actual wind turbine reliability. Descriptions of the failure classes and the wind turbine reliability scenarios assumed for the modeling calculations are given below.

Category 1: Manual restart

> This requires the physical presence of crew at the turbine in order to reset the turbine controller after it has been tripped by an alarm. This can occur relatively frequently, even in modern wind turbines, though once access to the machine has been secured, the duration of the visit is short. No actual repair operations to components are implemented for this category, though some level of investigation as to the cause of the alarm will often be required, causing some delay in restarting the machine.

Category 2: Minor repairs

> This category describes turbine failures caused by minor faults, typically involving sensor or instrumentation failure. Replacement of small parts may be necessary, as may some level of trouble-shooting in order to isolate the problem. Such small parts are assumed to weigh less than approximately 100 kg. This category of failure occurs at a similar level of frequency as manual restarts, but clearly requires more crew-time at the turbine before the repair is complete. Minor components may be transferred to the site by helicopter or service vessel and could require the use of the davit crane at the platform or the nacelle. It is likely that the majority of small parts will be significantly less than the aforementioned limit.

Category 3: Major repairs

> Here, more extensive work is required, usually to one of the major mechanical components of the turbine such as the gearbox, shaft bearings, blades, control systems or to electrical components such as the generator, converter, transformer, or switchgear. Although such failures will occur much less frequently than the previous two categories, in general they are likely to be relatively time consuming, with the turbine in question out of commission for multiple days. Helicopters are unsuitable for addressing such failure events due to the heavier parts and equipment that are required. In most cases, lifting gear mounted on the turbine itself will be sufficient to deliver the required parts and equipment to the nacelle and therefore jack-up vessels with external cranage will not usually be required.

Category 4: Major replacements

> In the early years of operation of a wind farm, any major component failures typically occur as a result of early life failures including perhaps some serial defects. Later in the project life, such occurrences are likely to be much less frequent. Lifting constraints will prevent the regular service crews from carrying out such operations and auxiliary plant and crew will be mobilized for the job. Typical operations include the replacement of gearboxes, generators, and transformers. In most cases, a jack-up vessel will be required for such operations, which will have a duration of 1-2 working days per turbine, given favorable weather conditions, plus a period of demobilizing.

Within the O2M Plus model, turbine reliability is described principally by the MTBF of each failure mode described below. Failure events are created by the O2M model stochastically, the frequency of which are determined (in the long-term) by the MTBF value. In reality, the reliability of any system may vary somewhat over its lifetime but, for the purposes of this study, the reliability assumptions have been assumed to remain constant throughout the project lifetime.

For the purposes of this study, GL GH has assumed a baseline reliability profile, the MTBF values of which are detailed in Table 7-2. The repair effort for the four fault types are also presented here in the form of the DTTR, as the total man-hours required to repair the fault, given turbine access and part availability.

Table 7-2: Assumed MTBF and DTTR for Baseline Reliability Profile

Failure Category	Description	MTBF[1] [hours]	Failure Rate [no/turb/yr]	DTTR[2] [hours]	Spares Required	Special Equipment
1	Manual restart	1000	8.8	4	-	-
2	Minor repair	2500	3.5	8	Minor comp.	-
3	Major repair	20000	0.44	70	Sub comp.	-
4	Major replacement	80000	0.11	90	Major comp.	Crane vessel

1. Mean Time Before Failure – quoted for individual turbines
2. Direct Time To Repair – man-hours to complete the repair given turbine access and parts availability.

Due to the uncertainty surrounding turbine reliability assumptions, impacts of the sensitivity of the simulation results to perturbations in failure rate inputs have been studied by varying the failure frequency by ±20% to give results for degraded and improved turbine reliability cases. The central, degraded and improved profiles are detailed in Table 7-3.

Table 7-3: Assumed Turbine Reliability for Central, Degraded and Improved Cases

Failure Category	Central MTBF [hours]	Central Failure Rate [no/turb/yr]	Degraded MTBF [hours]	Degraded Failure Rate [no/turb/yr]	Improved MTBF [hours]	Improved Failure Rate [no/turb/yr]
1	1000	8.8	833	10.5	1250	7.0
2	2500	3.5	2083	4.2	3125	2.8
3	20000	0.44	16667	0.53	25000	0.35
4	80000	0.11	66667	0.13	100000	0.09

It should also be noted that when utilized in this way, the O2M model results will not account for the impact of failures due to serial defects, which have occurred at several offshore wind farms to date. Ultimately, the turbine reliability assumptions discussed in this Section should be validated against fleet data provided by turbine manufacturers. However, for the purposes of the current study, the assumptions quoted here are considered to be sufficiently representative of a modern, proven wind turbine model.

Distance to O&M Port

The selection of a suitable operations base port is of vital importance to the optimal O&M of an offshore wind farm. In order to capture the perceived variation in project availability and OpEx with different transit times, three alternative distances between the project site and an O&M port have been modeled. It should be noted, however, that the distance to port has only been assumed to affect onshore-based access strategies and not the access strategies that involve the use of a floatel or an offshore base, which are assumed to be stationed in the vicinity of the project no matter what distance to the onshore base.

The distances to the O&M port modeled are presented in Table 7-4.

Table 7-4: Modeled Distances to O&M Port

Distance to O&M Port	Transit Time[1]
10 Nm (18.5 km)	~1 hour
30 Nm (55.6 km)	~2 hours
50 Nm (92.7 km)	~3 hours

1. Assuming typical work boats cruising speed of 20 knots (37 km/h) and mobilization time of 0.5 hours

It should be noted that the Installation and O&M LCoE Analysis Tool allows the assessment of any distance between the project site and an O&M port by interpolating between the results of these three alternative distances.

Jack-Up Contracting Strategy and Lead Times

Currently there is no experience in the utilization of jack-up vessels for offshore wind energy projects within the U.S. and therefore provision has been included in this analysis to study the impact of costs incurred when securing alternative jack-up contracting strategies.

The optimum approach to contracting of a jack-up vessel when required for major repair/replacement operations will depend on, among other factors, the reliability of the wind turbines, the site climate, the number of turbines composing the wind farm and the prevailing vessel market conditions at the time. Broadly speaking, the operator of an offshore wind farm will have control over a combination of fixed costs, variable costs, and associated lead times (duration from time of order to time that barge arrives at site ready for work) depending on whether an ‘Open Market’, ‘Call-off’, or ‘Ownership’ long-term commercial arrangement is in place with a vessel provider.

- In general, **Ownership** of a jack-up vessel results in the shortest lead times and therefore turbine downtime; however, this benefit comes as a trade-off with high annual fixed costs. For this study, this strategy has been modeled with a lead time of 3 days and a high annual fixed cost.
- On the **Open Market**, jack-ups can be contracted when they are required. Open market approaches generally have the longest lead times as quite often a wind farm operator will have to wait for the vessel to finish another job and mobilize to the site. On this strategy a mobilization and demobilization cost is incurred every time the vessel is called out, although the lead time is not guaranteed by contract. A day rate is also payable for the duration of the necessary works.
- Costs for a **Call-off** contract are generally expected to fall between those for the above-described Ownership and Open Market strategies. An annual retainer is paid to ensure a specified lead time or at least to minimize such lead times, though additional costs, albeit lower than those on the open market, are paid for each mobilization and demobilization of the vessel and for each day it is required.

For the purposes of the modeling conducted for this study, contracting strategy and lead times have been kept separate to allow the user to vary both parameters independently within the Installation and O&M LCoE Analysis Tool, although in reality the two are clearly linked. All unit cost assumptions (including jack-up related costs) are also amendable by the user as described in Section 7.3.9 and Appendix A.

Contracting Strategy

The three contracting strategies assumed are described in Table 7-5.

Table 7-5: Jack-up Barge Contracting Strategies

Option	Description	Strategy Assumptions
1	Ownership	Annual fixed cost
2	Call-off	Annual Retainer Mobilization and demobilization cost Average day rate
3	Open Market	Mobilization and demobilization cost Average day rate

Lead Times

As described above, the lead time from the order of a jack-up vessel to its arrival on site is highly uncertain. To assess the impact of variation in jack-up lead times, it was deemed pragmatic to model three alternative scenarios representing low, central, and high estimates. These were estimated as follows:

- The lowest modeled lead time is based on the assumption of jack-up vessel ownership and up-keep at a nearby port, for which a lead time of 3 days has been assumed to account for brief mobilization works and transit to site.
- A high estimate is more difficult to estimate as it will depend heavily on demand and availability for jack-up vessels as well as their distance from the project site. A nominal 'commercial' lead time of 30 days was assumed to represent a period of limited availability on the open market. To this was added an approximate transit time from the Gulf of Mexico to each region, since it is considered that an open market contracting approach is likely to draw on jack-up vessels normally operating in the Gulf of Mexico oil and gas sector.
- A central estimate was derived using a simple rounded average of the low and high estimates.

The assumed ranges of lead times for each region are presented in Table 7-6.

Table 7-6: Jack-up Vessel Lead Times Assumptions

Lead Time Scenario	Atlantic North	Atlantic Central	Atlantic South	Gulf of Mexico East	Gulf of Mexico West	Pacific South	Pacific North	Great Lakes
Low	3 days	3 days	3 days	3 days	3 days	3 days	3 days	3 days
Central	21 days	20 days	18 days	18 days	17 days	26 days	28 days	23 days
High	39 days	37 days	33 days	33 days	31 days	48 days	53 days	43 days

The proposed lead times are used to provide flexibility to the Installation and O&M LCoE Analysis Tool and should not be viewed as hard bounds. Jack-up vessel lead times are subject to considerable uncertainty and hence these values should be considered in this context. The Installation and O&M LCoE Analysis Tool has been configured to enable the user to interpolate to any lead time within the modeled range for each region.

O&M Strategic Dimensions

Four dimensions have been defined for the assessment of a potential offshore wind farm within the U.S. which constitute strategic O&M options and are thereby subject to post-simulation optimization within the Installation and O&M LCoE Analysis Tool. These are described below.

Access Strategy

The choice of access strategy is highly site specific, depending predominantly on the distance to the site and the metocean climate at and surrounding the site, though also on turbine reliability and project size. High accessibility to a site will increase the number of hours technicians have available to carry out work, resulting in a positive impact on availability. Often, however, a balance must be obtained between accessibility and vessel costs. After reviewing the existing and potential emerging access strategies (as described in Section 7.1), the following access strategies were modeled:

1 Port-based work boats (Work Boats)

Work boats are defined here as any vessels which return to an onshore base on a daily basis and therefore are assumed to cover those vessels outlined in Section 4.2.3. Based at an onshore port, this strategy employs vessels as the main method for accessing the site. The boats offer a relatively high passenger capacity and have the added benefit of lower running costs than helicopters. The boats are capable of transporting scheduled maintenance and repair crews, with a maximum capacity of 12 passengers. They are capable of carrying minor and medium-sized components to the site but not those required for a major repair / replacement, for which a jack-up vessel is required. The vessels are assumed to be restricted to wind speeds below 15 m/s (at 10 m amsl). In order to allow current and future development in work boat designs, the significant wave height (Hs) limits of these vessels has been varied in a range between 1.25 m and 2.0 m. This access strategy represents current standard practice for near-shore projects and may be used to assess the current state of the art as well as for benchmarking purposes against the alternative strategies below.

2 Port-based work boats plus helicopter (Helicopter Support)

This strategy utilizes a helicopter to transport crews between the O&M service base and the offshore wind farm site on occasions where weather precludes work boat access, resulting in higher accessibility relative to Access Strategy 1. The intention of this strategy is to mitigate the detrimental effects of the wave climate on availability. The helicopter is used for transporting crews (maintenance and repair) and minor components to the turbines and is subject to the wind and wave conditions at the site. Only one helicopter is available to access the project at any one time, although in reality this working regime may occasionally necessitate a second “courtesy” aircraft given the high maintenance burden to which helicopters are subject. It has been assumed that the helicopter cannot be used for major repairs or replacements (Categories 3 and 4 in Section 0) due to the large part sizes typically associated with these operations.

3 Mothership with daughter crafts (Mothership)

This strategy assumes the crews are based on a mothership within the vicinity of the project site and would normally be considered if the project is located far from the O&M port. It is assumed that a number of daughter crafts can be deployed from the mothership during relatively benign conditions, and that an access system (such as those described in Section 4.2.6) in conjunction with the mothership itself may be used during more onerous sea-states, improving the accessibility to the turbines. This mothership and access solution system provide the additional possibility of night-time working, subject to local and national consenting and regulations. Therefore, for this access strategy, it has been assumed that approximately 2/3 of the total number of crews dedicated to unscheduled repair works shall be deployed for the day shift, when daughter crafts or the mothership are available for transfer, while the remainder of the repair crews shall be assigned to night shifts, when it is envisaged that working guidelines would only allow access from the mothership. It is assumed that the mothership is used only to transfer technicians to the turbines for unscheduled maintenance operations whenever weather prevents these tasks from being carried out from the daughter crafts. Therefore, it is assumed that scheduled maintenance work is conducted only from daughter crafts and therefore only during the day time.

It is further assumed that technicians live on site utilizing a 2-week-on / 2-week-off system; living, eating and “off-shift” facilities are therefore required at the offshore base. Such a system will clearly reduce transport time, allowing more time for repair/maintenance work, ultimately resulting in increased availability. Unit staff costs will increase, as compensation for offshore working will be required; however, the potential increase in accessibility and shorter transfer times may justify a reduction in the number of crews required on shift at any one time. Meanwhile, the higher number of employees required to cover the greater amount of annual leave afforded offshore-based staff should also be considered. This is of course to be set against the additional capital and operational expenditure required for the mothership itself. Furthermore, shorter transport distances will reduce transport fuel costs, but journeys to shore will inevitably be a regular expense. It has been assumed that the mothership has adequate provision to store smaller parts, which can be re-stocked from the onshore service base as demand dictates.

4 Offshore-based personnel with work boats (Offshore Fixed Based)

Another approach suited to far-shore projects, this strategy involves the use of a permanent offshore base, located in the vicinity of the wind farm site, from which work boats transport crews the short distance to the turbines requiring repair or scheduled maintenance. Unlike Strategy 3 described above, the offshore base will not directly improve accessibility, since work boat transfer between the base and turbines will still be required, although the shorter transit times will mitigate weather risk to some degree. The work boats will either travel to the offshore base from the onshore O&M port prior to the start of the shift or will be deployed directly from the base itself by means of a launch and recovery system. The use of work boats has been assumed to preclude night working.

This offshore-based strategy shares the same assumptions regarding offshore shift patterns and facilities as Strategy 3 outlined above.

5 Jack-up vessel as an accommodation platform (Jack-up as offshore base)

This strategy attempts to mitigate some of the fixed costs associated with offshore working by utilizing a jack-up crane vessel to act as an accommodation platform in addition to its nominal O&M role for replacing major components. The jack-up vessel will operate as an offshore base, as described in Strategy 4, with the added capability of being used for major replacements.

Much like the fixed offshore base (Strategy 4), access to turbines is carried out via work boats, assumed to transit to the jack-up prior to the start of the shift. It is assumed the jack-up is nominally stationed adjacent to a turbine, substation, or other structure and hence may utilize the boat landing of that structure for transferring technicians between the jack-up and work boats. Unlike the mothership strategy, the weather limitations on jacking up and down are assumed to prevent direct access from the jack-up barge to the turbines in more onerous conditions.

This approach seeks to streamline costs by combining the cost of the jack-up for major replacements with the cost of offshore accommodation. It should be noted that this strategy is only modeled in conjunction with jack-up *Ownership* contracting strategy (see Section 0).

6 Port-based work boats plus hovercraft (Hovercraft Support) (Great Lakes Region only)

This strategy is only assessed for the Great Lakes region in which ice coverage is a limiting factor for access during winter months. The strategy utilizes a hovercraft to transport crews between the onshore O&M service base and the project site on occasions where ice precludes work boat access, resulting in higher accessibility relative to Access Strategy 1. The intention of this strategy is to mitigate the detrimental effects of ice coverage on availability. The hovercraft is used for transporting crews and minor components for unscheduled maintenance activities and is subject to the wind conditions at the site. Only one hovercraft is available to access the project at any one time, although in reality this working regime is likely to necessitate a second hovercraft on a rotation system given the very high maintenance burden to which hovercraft are subject. It is assumed that hovercrafts can carry 12 passengers (excluding vessel crew) and cannot be used for operations requiring major replacements (failure Category 4 in Section 0).

Vessel Significant Wave Height Capabilities

Several work boat or service vessel designs are available for offshore wind farm O&M activities in the current market, covering a range of cost and specification. Differences in the safe sea-state limit for personnel transfer (Hs limit) will impact achieved availability levels as well as instigate differences in capital and operational costs. While described as a work boat operating limit, this parameter can also be used to model alternative marine transportation, such as SWATH vessels or work boat-mounted access systems, provided representative unit cost assumptions are made accordingly. In order to capture the impact of such variations on project performance, four options have been modeled, as outlined in Table 7-7.

Table 7-7: Vessel Hs Capabilities

Option	Description	Hs Limit [m] (Service Vessels)	Hs Limit [m] (Daughter Crafts)
1	Current standard practice	< 1.25	< 0.75
2	Current state of the art	< 1.5	< 1.0
3	Improved vessel design or access system	< 1.75	< 1.25
4	Greatly improved vessel design with access solution	< 2.0	< 1.5

Clearly, access from vessels is not only governed by Hs, with factors such as current, wave period, wave direction, and the nature of the swell also affecting vessel dynamics and hence transfer limitations. However, operators will typically use significant wave height forecasts and on-site measurements to determine whether to journey to site at a particular time and hence consideration of these additional interacting factors is outside the scope of work conducted for this analysis. Ultimately the vessel's skipper and each individual technician have the final decision regarding whether conditions are deemed suitable for transfers to commence.

It is noted that only Option 1 above has been consistently proven at offshore wind farms to date and results for the other three options are therefore included to capture the potential improvements in service vessels and equipment and should thus be viewed with a degree of caution.

Vessel Speed Capabilities

In addition to the safe sea-state limits for personnel transfer (Hs limit), the speed of service vessels used to transport technicians to the wind turbines will impact on transit times and consequently project availability. Many vessel providers quote maximum speeds in calm conditions, though true transit speeds are typically below this value due to the impact of waves, fuel economic operations and speed restrictions in harbors and channels. In order to capture the impact of a potential improvement in vessel speeds on project performance, two options have been modeled, as outlined in Table 7-8.

Table 7-8: Vessels' Speed Capabilities

Option	Description	Cruising Speed[1]
1	Current typical vessel (and hovercraft) speed	20 knots
2	Improved vessel (and hovercraft) speed	30 knots

1. Cruising speed assuming average conditions for transit to site and insignificant speed restrictions en route

It is noted that this improvement in speed is only applied to onshore-based access strategies (Work Boats, Helicopter Support and Hovercraft Support as described above) since any offshore accommodation is assumed to be located near the site and therefore an improvement to vessel speed would have an insignificant impact on transit times for offshore-based access strategies.

Repair Resources

The optimum number of crews dedicated to unscheduled repair operations depends on a large number of factors, not least the metocean climate, access strategy, and number of turbines being considered. Clearly, having a large crew resource is inefficient if the chosen access strategy is not capable of transporting them, when required, to the wind farm for a high proportion of the time. Under such a scenario, adopting a small crew resource with fewer, higher specification vessels could be a more economical option. The unscheduled repair resourcing dimension was therefore varied within the analysis from 3 to 18 crews to account for these inter-dependencies.

It has been assumed that there are always a sufficient number of work boats or daughter crafts for all modeled technicians to access the site at the same time during suitable conditions. This assumption is deemed prudent to avoid inefficiencies in the strategic approach. Therefore the number of work boats or daughter crafts is scaled with total scheduled and unscheduled crew resource.

Summary of Dimensions

Table 7-9 contains a summary of dimensions explored within the O2M multi-dimensional analysis, both those strategic dimensions which can be optimized in the Installation and O&M LCoE Analysis Tool and those project dimensions which cannot. The intention in defining these dimensions and variables is to capture the broad O&M strategic and project envelope available to developers of potential offshore wind projects within the U.S.

The dimensions presented in Table 7-9 are varied in all possible combinations, culminating in a total of 462,240 individual simulations.

Table 7-9: Summary of Project and Strategic Dimensions

Dimension	Type	Nº Options	Option							
			1	2	3	4	5	6	7	8
Coastal Regions	*Non-Optimized*	8	Atlantic North	Atlantic Central	Atlantic South	Gulf of Mexico East	Gulf of Mexico West	Pacific South	Pacific North	Great Lakes
Metocean climates	*Non - Optimized*	3	Low	Central	High					
Project Configuration	*Non-Optimized*	2	126 x 4 MW	84 x 6 MW						
Distance to O&M Port	*Non-Optimized*	3	10 Nm	30 Nm	50 Nm					
Turbine Reliability	*Non-Optimized*	3	Degraded	Central	Improved					
Jack-up Contracting Strategy	*Non-Optimized*	3	Open Market	Call-off	Ownership					
Jack-up lead times	*Non-Optimized*	3	Low	Central	High					
Access Strategy (Operational philosophies)	*Optimized*	5	Work Boats	Helicopter Support	Mothership	Offshore Fixed Base	Jack-up as Offshore Base	Hovercraft Support[1]		
Work boat capability (daughter craft in parentheses)	*Optimized*	4	Hs < 1.25 (Hs < 0.75)	Hs < 1. 5 (Hs < 1.0)	Hs < 1. 75 (Hs < 1.25)	Hs < 2.0 (Hs < 1.5)				
Work boat Speed	*Optimized*	2	20 knots	30 knots						
Number of repair crews	*Optimized*	6	3	6	9	12	15	18		

1. Hovercraft Support modeled only for the Great Lakes Region.

7.2.2 Other Assumptions

Other than those assumptions associated with the dimensions examined in this analysis as described in Section 7.2.1, a number of other assumptions were required. These simulation assumptions were fixed in all cases unless otherwise stated and are based on GL GH in-house knowledge of current industry best practice.

Other Access Constraints

For some wind farm sites, tidal constraints exist either at the project site or at the service base. Because of the broad areas considered in the model and the high level nature of this study, there are no specific ports under consideration to act as the O&M base for a wind farm within the U.S.; therefore, it has been assumed that the mean water depth at any of the potential ports is sufficient for no tidal restrictions to exist for the type of vessels typically employed for offshore wind farm O&M. Consequently, tidal constraint modeling has not been implemented.

Crews and Shift System

The crews have been broken into two sub-categories: those dedicated to scheduled maintenance (service crews) and those dedicated to undertaking unplanned corrective maintenance work (repair crews). For scheduled and unscheduled maintenance, 3 technicians per crew are assumed working 7 days per week, with a shift length of 12 hours.

It should be noted that for the purposes of the simulations, technicians are assumed to not require annual leave, sick days, etc. Account of this 'in-efficiency' is made by the estimation of a Full-Time Equivalent (FTE) factor. This FTE acts as a multiplier to calculate the true number of real technicians from the modeled workforce (see Section 7.3.2 for a description of how this FTE is calculated).

Scheduled Maintenance Crews

The service resource requirement is based on an assumption of the number of man-hours per turbine per annum necessary to perform an appropriate level of scheduled maintenance. These scheduled maintenance effort assumptions are given in Table 7-10 and assume that all necessary scheduled work is undertaken during the summer months.

Table 7-10: Assumed Turbine Service Effort Requirement

Wind Turbine Option	Man-hours per Turbine per Annum
Generic 4 MW	132
Generic 6 MW	160

In order to achieve this service interval for each combination of project and strategic dimensions, the number of scheduled service crews is subject to a pre-optimization process prior to running the simulations. The number of service crews is thus optimized for each project configuration, distance to port, and access strategy and work boat capability with a target mean maintenance interval of 1 year. In order to minimize production loss during the winter period it has been assumed that scheduled maintenance activity is carried out between the months of April and September.

Note that for all access strategies, scheduled maintenance is assumed to be performed via service vessels or daughter crafts, as the scheduled nature of such work should not lead to the accruement of downtime due to access restrictions, and hence the added operating costs of helicopters or large vessels are not considered justifiable for such purposes.

Unscheduled Maintenance Crews

The number of unscheduled maintenance crews has been varied as part of this analysis in order to capture the different resourcing requirements of alternative project and strategic options (see Section 0)

Energy Production Assumptions for the O&M Analysis

It is necessary to estimate approximate energy production of the two generic 504 MW projects, assuming 100% availability, thereby allowing the O2M Model to capture the differences between time-based availability and production-based (energy) availability. Clearly, during periods of high wind, turbines will be generating at close to capacity; however, it is also likely to be harder to access turbines during these times. This can lead to a tendency for longer periods of downtime that coincide with periods of high potential production. Therefore, energy availability, which takes this phenomenon into account by accruing lost energy production as opposed to downtime, is considered to be the more useful metric. Furthermore, as discussed in Section 7.2.1, an estimate of lost production due to downtime is required such that OpEx and lost production costs may be combined to identify optimal O&M strategies.

As described in Section 8, GL GH has developed a model to assess the wind farm Annual Energy Production (AEP), taking account of key technical and environmental criteria affecting the wind farm energy production. This model has been used to estimate the lost production accrued during periods of turbine downtime. In this manner the model calculates energy availability estimates as well as the "opportunity costs" which arise due to lost production as a result of turbine downtime, given an input energy sales price.

Vessels and Transport

GL GH has made a set of assumptions governing the operation and deployment of the work boats, jack-up vessels, mothership, daughter crafts, helicopters, and hovercrafts as described below.

- Work boats (scheduled & unscheduled maintenance)

Reaction and mobilization time	30 min
Cruising speed in average conditions	Varied (20 - 30 knots)
Vessel capacity (excluding vessel crew)	12 passengers
Wave limit for operation (Hs)	Varied (1.25 – 2.0 m)
Wind speed limit for safe personnel transfer	<15 m/s at 10 m amsl
Operability in sea ice	No

○ Working shifts	Day
○ Used for scheduled or unscheduled maintenance	Both
○ Part sizes carried (see Section 4)	Small / Medium

- Jack-up vessel

○ Wave limit for operation (Hs)	< 1.5 m
○ Wind speed limit for safe personnel transfer	< 10 m/s at 10 m amsl
○ Can operate in sea ice	No
○ Working shifts	Day & Night
○ Used for scheduled or unscheduled maintenance	Unscheduled
○ Part sizes carried (see Section 4)	Large

- Mothership

○ Reaction and mobilization time	30 min
○ Cruising speed in average conditions	12 knots
○ Wind speed limit for safe personnel transfer	< 15 m/s at 10 m amsl
○ Wave limit for safe personnel transfer (Hs)	< 2.5 m
○ Operability in sea ice	No
○ Working shifts	Day & Night
○ Used for scheduled or unscheduled maintenance	Unscheduled
○ Part sizes carried (see Section 4)	Small / Medium
○ Equipped with access solution system	Yes

- Daughter crafts

○ Reaction and mobilization time	30 min
○ Cruising speed in average conditions	20 knots
○ Vessel capacity (excluding boat crew)	6 passengers
○ Wind speed limit for safe personnel transfer	< 10 m/s at 10 m amsl
○ Wave limit for operation (Hs)	Varied (0.75 – 1.5 m)
○ Operability in sea ice	No
○ Working shifts	Day
○ Used for scheduled or unscheduled maintenance	Both
○ Part sizes carried (see Section 4)	Small

- Helicopter

Reaction and mobilization time	30 min
Cruising speed in average conditions	135 knots
Passenger capacity (excluding air-crew)	3 passengers
Wind speed limit for safe personnel transfer	< 15 m/s
Operability in sea ice	Yes
Working shifts	Day
Used for scheduled or unscheduled maintenance	Unscheduled
Part sizes carried (see Section 4)	Small

- Hovercraft

Reaction and mobilization time	30 min
Cruising speed in average conditions	Varied (20 - 30 knots)
Vessel capacity (excluding air-crew)	12 passengers
Wind speed limit for safe personnel transfer	< 10 m/s at 10 m amsl
Operability in sea ice	Yes
Working shifts	Day
Used for scheduled or unscheduled maintenance	Unscheduled
Part sizes carried (see Section 4)	Small/Medium

As described in Section 0 the number of work boats or daughter crafts is varied from simulation to simulation in the multi-dimensional analysis with the number of crews, ensuring there are always enough vehicles to transport all crews on duty simultaneously, if required.

Balance of Plant Downtime

A consideration which is not captured in the O2M Model is that of downtime due to electrical failures associated with connecting the wind farm to the electrical grid. Due to the high level nature of this study, GL GH has not conducted a detailed assessment of the impact of the maintenance of the balance of plant. However, an estimate of energy loss of 1% (i.e. 99% availability) will be applied across all dimensions discussed above based on past studies and industry findings.

Parts Store

GL GH has made a set of assumptions governing the location and operation of the parts store. The parts store location is assumed to be adjacent to the respective service base. GL GH also assumes the part store holds an unlimited number of each spare part, neglecting the re-order time associated with obtaining replacement spare parts from the manufacturer. Therefore, downtime due to parts shortages has not been considered in this study. In general, a well-managed wind farm should not suffer significant downtime due to parts shortages, supporting this approach.

7.3 Unit Cost Assumptions

In order to estimate the total operational cost for the generic offshore wind farm, it is necessary to make several assumptions on the cost of elements within the O&M infrastructure as well as other non-technical items such as insurance and administration. GL GH has made the following basic costing assumptions based on in-house knowledge and market intelligence.

The estimation of operating cost encompasses the cost of facilities – offices and storage, all personnel including administrative staff, all equipment such as boats, tools, and Personal Protective Equipment (PPE), servicing consumables and spares, and contracting of particular equipment for special repairs.

This O&M budget estimate does not include:

- Financing costs;
- Senior management costs; and
- Costs due to mistakes and inefficient O&M planning and implementation.

For the purpose of this work, preliminary costing of each O&M cost center has been completed, with details of the most significant provided below.

Some of the unit cost variables, such as jack-up vessel costs, insurance, and transmission network use-of-system charges, are subject to a high degree of variability, but the below estimates are considered reasonable approximations in the current context. It is recommended that the DOE considers each of these unit cost assumptions carefully in the context of a potential offshore wind energy market and that where necessary, additional information be gathered from relevant contractors.

It must be noted that all unit cost assumptions can be amended by the user in the Installation and O&M LCoE Analysis Tool to reflect projected future variations, project-specific data and to perform sensitivity studies.

7.3.1 General

Energy Revenue

Given the current uncertainty regarding future payment mechanisms for offshore wind generated electricity within the U.S., a rate of $200/MWh inclusive of all potential incentives has been assumed. GL GH has assumed this value to be constant for the duration of all simulations conducted.

Insurance

Costs related to operational insurances for an offshore wind farm are highly variable and will depend on the technology utilized, the location of the project, and the extent of the policy purchased. Based on experience with early offshore wind projects, GL GH has assumed a cost of $15,600 / installed MW / year.

O&M Service Provider Profit & Risk Margin

O&M service providers – whether they are the turbine supplier, the project owner or a third party contractor – will typically charge a mark-up on the resources provided to satisfy profit and risk margins. For the purposes of this analysis, GL GH has assumed a default value of a 20% increase to the cost of personnel, vessels, helicopter, jack-up, floatel and parts and consumables. As with all unit cost assumptions, this percentage can be varied by the user in the Installation and O&M LCoE Analysis Tool.

Fees and Leases

The use of Seabed and of the Transmission Network System is a relevant annual cost that operators must bear in mind. For the purposes of this analysis, a value of $4,000,000 per annum has been assumed for the Seabed lease based upon experience in Europe, while no fees have been applied for the use of the Transmission Network System, although this may be defined by the user of the Installation and O&M LCoE Analysis Tool as required.

7.3.2 Technicians

Costs related to technicians consist mainly of salaries, medical cover, pension, subsistence, training, and equipment. An average salary of $54,600 per annum has been assumed for each offshore service personnel for a 40-hour week.

The O2M Model assumes that technicians (as simulated) do not require sick allowance, annual leave, or public holidays. As a result, a factor is applied to a technician's salary to realistically account for the actual number of 'real world' employees required to cover the work as simulated. The estimates made by GL GH in calculating such a factor are summarized in Table 7-11.

Table 7-11: Estimating the Full-time Equivalent Factor for Service Technicians

Item	Assumption		Comments
Employee average salary	54,600	$/annum	Typical for current market
Employee work rate	40	Hours per week	
Ideal working days	260	Days per year	Assumes 5-day week
Holiday allowance	25	Days per year	Typical allowance
Public holiday entitlement	8	Days per year	Current provision
Sickness allowance	7	Days per year	Typical private sector
Actual working days	220	Days per year	
Actual working hours	1,760	Hours per year	(A)
Simulated working days	365	Days per year	
Simulated work rate	84	Hours per week	
Simulated working hours	4,380	Hours per year	(B)
FTE Factor	2.48		Full-time Equivalent (B/A)

A factor of 2.48 has therefore been applied to the technicians' salary above to reflect the real-world cost of achieving the resourcing as modeled. This FTE factor may be applied to the number of technicians quoted in this work to estimate the number of full-time employees required to provide O&M support to the project.

In addition to salaries, there are overhead costs associated with employing each technician including, but not limited to, recruitment, insurances, pensions, benefits, and head office administration. To this effect an employment overhead of 30% has been applied to each technician. Also, an allowance of $3,900 per employee per annum has been made to cover training and the provision of equipment.

Anticipating that crews based offshore will require an increase in salary due to the extended periods away from home as well as the inclusion of night shifts within the working regime, a multiplier of 1.5 has therefore been applied to all crews when an offshore base, mothership, or jack-up vessel is utilized for the purposes of offshore-based working.

Generally, technicians employed directly by the operator or OEM will carry out day-to-day work on the wind turbines solely, i.e. scheduled and unscheduled maintenance. Additional personnel or contractors will be employed for inspection and repair work in relation to Balance of Plant elements as described in Section 7.3.11.

The total technician cost is therefore assumed to be $211,004 and $273,918 per annum per modeled onshore-based and offshore-based technician, respectively.

7.3.3 Onshore Base and Administration

Allowances have been made for the operational costs associated with an onshore base and day-to-day administration of a generic project. These comprise staffing, office, and parts storage costs, as described below.

Staffing

Basic administrative facilities and staffing are required to operate and maintain an offshore wind farm. The tasks to be carried out during the operational life of a wind farm include but are not limited to: remote monitoring, coordination of maintenance, stock management, and coordination of maritime traffic. Full-time onshore staffing and salary estimates for both wind farm configurations are outlined in Table 7-12.

Table 7-12: Onshore Staff Salaries

Position	Average Salary [$]	Quantity
O&M Manager	93,600	1
Service & HSE Coordinator	65,000	1
Store Manager	45,500	1
SCADA / CMS Engineers	45,500	2
Administrative Assistants	41,600	3

No formal training or specific equipment needs are anticipated for these staff within the project O&M budget; however, the same employment overheads applied to offshore technicians are relevant, for which 30% has been applied to each staff member's salary.

Therefore, the total cost assumption for onshore staff is $546,000 per annum.

Office

Clearly, the nature of the onshore facilities will be somewhat project specific and depend on factors such as available area at the chosen port, access strategy and number of turbines. However, for the purposes of this study it is estimated that approximately 300 m^2 is necessary to cover office space, meeting room, mess room, kitchen and changing facilities for the generic offshore wind farm. A nominal cost of $312 per m^2 per annum has been assumed for leasing, with a further $156 per m^2 per annum for running costs, resulting in an annual cost of $140,400 for office space.

Some allowance for additional space for facilities such as showers and toilets, along with general running costs have been made in the onshore base cost estimate.

Parts Store

Usually adjacent to the onshore office, a store will be required for the replacement components held for any of the projects. A fixed allowance of 1,000 m^2 has been estimated to provide a workshop and basic staff facilities, based on GL GH knowledge and experience. Annual costs are assumed to comprise $93 per m^2 for space rental and $31 per m^2 for running costs (consisting predominantly of power requirements).

Quayside space will be required for temporary storage of parts, loading and unloading of support vessels. An area of 400 m^2 has been deemed to be sufficient to support the wind farm. Annual costs are assumed to comprise $156 per m^2 for space rental.

A summary of the assumptions made by GL GH for an onshore base is provided in Table 7-13.

Table 7-13: Cost Assumptions – Onshore Base

Cost Item	Cost Assumption / Salary	Unit	Quantity
Staff			
O&M Manager	$93,600		1
Service & HSE Coordinator	$65,000		1
Stores Manager	$45,500		1
SCADA / CMS Engineers	$45,500		2
Administrative Assistants	$41,600		3
Employment Overheads	30%		
Onshore based staff costs	$546,000	/ annum	
Onshore Office			
Office Ground Space	300	m^2	
Lease Space	$312	/ m^2/ annum	
Running Cost	$156	/ m^2 / annum	
Total Office Cost	$104,400	/ annum	
Onshore Parts Store			
Warehouse Space	1,000	m^2	
Lease Space	$93	/ m^2 / annum	
Running Cost	$31	/ m^2 / annum	
Total Warehouse Cost	$124,000	/ annum	
Quayside Costs			
Quayside Space	400	m^2	
Leasing Cost	$156	/ m^2 / annum	
Total Quayside Cost	$62,400	/ annum	

7.3.4 Work Boats and Daughter Crafts

As described in Section 0, in order to assess the impact on accessibility to the wind farm when improving the work boat and daughter craft capabilities, and to consider further vessel design development (such as SWATHs or vessel-mounted access systems, etc.), the model has considered a variety of vessel designs. Based on industry experience and consultation with providers of such vessels, the vessel capabilities together with their estimated annual costs for the assumed long-term contracts are shown in Table 7-14. A marine diesel cost assumption of $4.00 per gallon has been assumed.

Table 7-14: Cost Assumptions – Service Vessels

Description	Cruising Speed[1]	Hs limit	Unit Cost[1] [$/annum]	Fuel Consumption [gallons/hour]
Daughter Crafts (6-passenger capacity)				
Design 1 (Current industry standard)	20 knots	Hs < 0.75 m	490,000	10
Design 2 (Current state of the art)	20 knots	Hs < 1.00 m	550,000	30
Design 3 (Improved design)	20 knots	Hs < 1.25 m	610,000	50
Design 4 (Greatly improved design)	20 knots	Hs < 1.5 m	660,000	70
Work Boats (12-passenger capacity)				
Design 1 (Current industry standard)	20 knots	Hs < 1.25 m	600,000	40
Design 2 (Current state of the art)	20 knots	Hs < 1.50 m	1,000,000	50
Design 3 (Improved design)	20 knots	Hs < 1.75 m	2,000,000	92
Design 4 (Greatly improved design)	20 knots	Hs < 2.00 m	3,000,000	132
Design 5 (Faster vessel)	30 knots	Hs < 1.25 m	700,000	52
Design 6 (Faster state of the art vessel)	30 knots	Hs < 1.50 m	1,500,000	79
Design 7 (Faster, improved vessel)	30 knots	Hs < 1.75 m	2,500,000	118
Design 8 (Faster, greatly improved vessel)	30 knots	Hs < 2.00 m	3,500,000	171

1. Cost per vessel based on a long-term lease with skipper and crew included.

7.3.5 Hovercraft

For the Great Lakes region where an additional access strategy has been modeled, a hovercraft is used for unscheduled repairs during periods of sea ice coverage. A relatively large, 12 PAX hovercraft has been assumed to ensure sufficient durability to withstand the demanding sea ice environment. While the details of the precise nature of the vessel or the likely approach to contracting remain unclear, an annual rate of $1,800,000 has been assumed to cover the vessel, crew, and maintenance for a long-term contract. Fuel usage has been assumed to be around 21 gallons of fuel per hour of travelling, based on specifications for the Griffon 2000TD hovercraft [24]. As with the work boats, marine diesel has been assumed to cost around $4.00 per gallon.

7.3.6 Helicopter

GL GH has applied costing assumptions based on previous discussions with suppliers and operators for the helicopters considered in this analysis. It is anticipated that helicopters will be implemented on a charter basis, for which costs are divided into an assumed annual fee of $1,950,000 which covers the cost of the aircraft and maintenance burden and an hourly fee of $1,105 to cover fuel and pilot / co-pilot crew.

7.3.7 Mothership

GL GH has applied costing assumptions based on previous discussions with suppliers and operators of motherships and offshore support vessels. It is anticipated that a mothership will be implemented on a long-term charter basis, for which a basic annual cost of $7,800,000 has been assumed. On top of this are further unit cost assumptions for living costs, support staff, the access system, and fuel, as summarized in Table 7-15.

Table 7-15: Cost Assumptions – Mothership and Auxiliaries

Cost Item	Cost	Unit
Mothership		
Annual Fixed Cost	$7,800,000	/ annum
Living Cost	$78	/ person / day
No. Support Staff	8	personnel
Support Staff Salary	$46,800	/ person / annum
Support Staff Overheads	30%	
Access System OpEx	$2,500,000	/ annum
Transport Costs		
Fuel Oil Price	$1,142 ($1,028)	/metric tons (/ short ton)
Fuel Consumption (travelling)	0.38 (0.35)	metric tons /hour (short tons / hour)
No. of Trips to Port	2	trips / month
Fuel Consumption (auxiliaries)	0.13 (0.12)	metric tons /hour (short tons / hour)

7.3.8 Fixed Offshore Base

Based on in-house knowledge and market intelligence, GL GH has applied costing assumptions for the fixed offshore base. It has been assumed that an offshore base will incur a basic annual cost of $11,700,000 to cover annualized CapEx and OpEx requirements. On top of this are further unit cost assumptions for living costs of technicians and support staff, as summarized in Table 7-16.

Table 7-16: Cost Assumptions – Offshore Base

Cost Item	Cost	Unit
Annual Fixed Cost	$11,700,000	/ annum
Living Cost	$78	/ person / day
No. Support Staff	8	personnel
Support Staff Salary	$46,800	/ person / annum
Support Staff Overheads	30%	

7.3.9 Jack-up Vessel

As described in Section 7.2.1, costs associated with jack-up vessels are heavily dependent on the contracting strategy undertaken. The cost assumptions made by GL GH for this analysis are described below.

Ownership Strategy

Under a jack-up *Ownership* strategy it is considered that there would be an associated annual cost for the general maintenance and berthing of the vessel. However, if the jack-up is to be used solely for a single project, the annual cost of the vessel should reflect the amortized capital expenditure as well as the associated running costs. For the ownership contract strategy, an estimated cost of $20,800,000 per annum has been assumed. It should be noted that when selecting the jack-up as accommodation base, the model always assumes an *Ownership* contract strategy.

Call-off Contract Strategy

Costs for a C*all-off* contract are generally expected to fall between those for Ownership and Open Market strategies. An annual retainer is paid to ensure a specified lead time, though additional costs are paid for each mobilization and demobilization of the barge and for each day it is required. The assumed costs for this strategy are:

Annual fee:	$468,000 / annum
Mobilization plus demobilization cost:	$312,000 / event
Average day rate:	$140,400 / day

Open Market Strategy

On the *Open Market*, jack-up costs can vary considerably. A mobilization and demobilization cost is incurred every time the vessel is called out, although the lead-time is not guaranteed by contract. A day rate is also payable for the duration of the necessary works. It is important to note that the long lead times under this contract strategy have a significant impact on the wind farm availability and consequently on the lost production of the project.

Mobilization plus demobilization cost:	$312,000 / event
Average day rate:	$140,400 / day

7.3.10 Spare Parts and Consumables

Due to the large number of components exposed to potential failure in a wind turbine, four broad failure categories have been derived by GL GH for use in the O&M analysis.

Using in-house knowledge and experience, GL GH has derived average cost estimates for replacement spare parts provision for each of the three failure categories (2-4) which involve replacement of parts, as detailed in Table 7-17 below. For the purposes of the O&M analysis, no costs of potential overhauls have been considered, though it is possible to specify the cost of parts and overhauls per turbine per annum in the Installation and O&M LCoE Analysis Tool.

Table 7-17: Cost Assumptions – Replacement Parts

Failure Category	Part Required	Unit Cost [$]	
		4 MW	6 MW
1. Manual restart	None	-	-
2. Minor repair	Minor component	2,080	3,432
3. Major repair	Sub component	13,130	21,840
4. Major replacement	Major component	224,640	374,400
Scheduled Maintenance	Consumables	10,270	17,160

7.3.11 Balance of Plant

Cable Maintenance

Submarine cables shall be subject to regular monitoring surveys and potentially repair and reburial operations. The interval of the surveys will be determined by regulations, burial depth, seabed movement, and traffic and activity along the cable route and in the wind farm. It is generally recommended that a full survey of the entire cable length be carried out every year in the first three years, and then perhaps every 2-5 years for the remaining lifetime of the project. However, it should be noted that the results from the initial surveys as well as the local site conditions shall inform the frequency of subsequent surveys.

Electrical Plant Maintenance

Inspection and scheduled maintenance for the substation topside and electrical equipment will vary significantly depending on the technology chosen. Following inspections it is anticipated that a number of repairs will be required each year.

Support Structure Maintenance

The O&M activities in relation to the support structures are not trivial. These will depend on the foundation type and include but are not limited to:

- Inspection and repair of paint protection (monopile, jacket);
- Inspection, cleaning and repair of boat landing and access platform;
- Control and maintenance of corrosion protection systems (monopile, jacket);
- Inspection and repair of scour protection (monopile, gravity base structure); and
- Inspection and testing of welds and joints (jacket, monopile).

Inspection of the paint protection, joints and appurtenances, and scour protection is likely to be required every three years. This is to include divers, dive boat, and a standby boat. Every few years, following the inspection, repairs to the paint protection and scour protection might be necessary. Furthermore, repainting of the turbine tower is likely to be required once during the lifetime of the project.

Miscellaneous Maintenance

Regulatory requirements will impose third party inspection of personnel lifts, ladders, davit cranes, fall arrest devices and winching equipment in the wind turbines. Based on the assumptions outlined above, the total cost estimate to cover Balance of Plant O&M has been assumed to be $18,000 per turbine per annum to cover scheduled works, with a further $5,800 per turbine per annum to cover unscheduled repairs.

Environmental Surveys

Due to certain environmental concerns such as bird collision or impact on wildlife, projects are required to follow environmental studies during the first years of operations. To account for these activities, an assumed cost of $400,000 per annum has been included in the model.

Wind Turbine Power Consumption

In order to run auxiliary components such as computers, communications, controlling and emergency devices, wind turbines consume a small amount of electricity which has been assumed to incur a cost of $2,000 per turbine per annum.

8 ANNUAL ENERGY PRODUCTION

GL GH has developed a set of functions to calculate the annual energy production (AEP) for a generic 504 MW project which takes account of changes in project characteristics such as wind turbine capacity, wind climate and inter-turbine spacing. These functions are used to determine the Net Capacity Factor (NCF) across U.S. waters as a function of mean wind speed and project installed density (inter-turbine spacing). All the assumptions and considered scenarios for this assessment are described in the following sections.

8.1 Wind Climates

The energy production of a project is dependent on a number of variables, the most important of which is the long-term wind climate at the location of the turbines. Given the requirement to characterize the wind climate across each of the U.S. coastal regions described in Section 2, GL GH used the three 33-year wind data time series collated (as described in Section 5) in each coastal region and scaled them from 10 m above MSL to a hub height of 100 m. This scaling was performed assuming a boundary layer power law exponent of 0.11.

8.2 Wind Turbine Performance Characteristics

The turbine models used in the analysis are based on GL GH-derived 4 MW and 6 MW generic models. The characteristics and performance data of these turbines are presented in Table 8-1.

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Table 8-1: GL GH Derived Power Curves for the Generic Wind Turbines Considered

Wind Speed at Hub Height [m/s]	Electrical Power [kW] Generic 4 MW Turbine	Electrical Power [kW] Generic 6 MW Turbine
3	0.0	0.0
4	0.0	0.0
5	387.0	610.3
6	668.7	1082.4
7	1061.8	1718.8
8	1584.9	2565.7
9	2261.2	3653.2
10	3167.6	5185.4
11	4000.0	6000.0
12	4000.0	6000.0
13	4000.0	6000.0
14	4000.0	6000.0
15	4000.0	6000.0
16	4000.0	6000.0
17	4000.0	6000.0
18	4000.0	6000.0
19	4000.0	6000.0
20	4000.0	6000.0
21	4000.0	6000.0
22	4000.0	6000.0
23	4000.0	6000.0
24	4000.0	6000.0
25	4000.0	6000.0
Rotor diameter [m]	120	155
Cut-out 10-minute mean wind speed [m/s]	25	25
Restart 10-minute mean wind speed [m/s]	22.5	22.5

Figure 8-1 depicts the performance of a variety of turbine offerings to the European offshore wind market in terms of capacity factor (generator utilization) and the rotor productivity, assuming a characteristic wind climate. Based on these offerings, turbines can be grouped into the following performance categories:

- A **large Rotor** to small generator ratio (defined here as 'Type **R**');
- A small rotor to **large Generator** ratio (defined here as 'Type **G**'); and
- A **Central** case between the two above extremes (defined here as 'Type **C**').

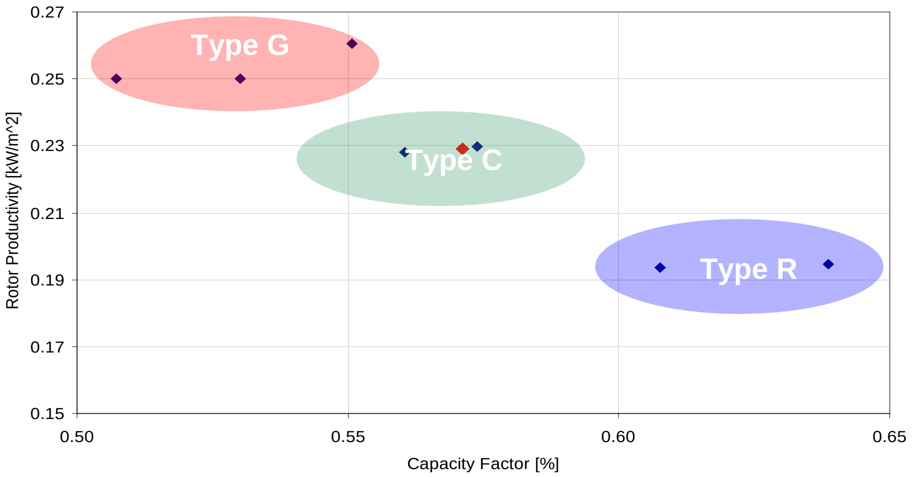


Figure 8-1: Wind Turbine Capacity vs. Rotor Productivity

The two primary design parameters for wind turbines can be considered to be the size of the rotor and the capacity of the electrical plant. Both of these parameters can be regarded to be a constraint on production. At low wind speeds the maximum amount of energy that can be generated is limited by the size of the area from which the turbine can capture the free flowing energy in the wind. At higher wind speeds, it is the electrical plant which constrains the amount of power that can be produced.

It can be considered that the interrelationship between the above mechanical and electrical characteristics and their costs will determine the optimal turbine design for a given site. Recent market trends suggest that wind turbine manufacturers in Northern Europe are opting for large-rotor-to-small-generator machines; therefore, for the purposes of this assessment, GL GH has developed turbine performance data that best represent ‘Type R’ characteristics.

8.3 Generic Project Layouts

GL GH has made the following assumptions regarding the generic project used in the development of the AEP functions:

- Generic project with a total capacity of 504 MW;
- Projects are assumed to occupy a rectangular boundary which varies according to the turbine capacity, considering the following arrays:
    - 14 columns and 9 rows of 4 MW turbines (126 units);
    - 12 columns and 7 rows of 6 MW turbines (84 units); and
- A uniform in-row and inter-row spacing is assumed for all turbine layouts.

GL GH considers that large-scale deployment of offshore wind will drive projects to operate with larger turbine spacing than current industry practice, in an attempt to minimize wake losses within large arrays. GL GH has therefore investigated three different generic layouts with turbine spacing of 8D, 10D, and 12D (where D is the turbine rotor diameter), resulting in six array densities ranging from 2.2 MW/km^2 up to 5.3 MW/km^2 depending on the wind turbine size. The power density of each considered layout is shown in Table 8-2.

Table 8-2: Variation in Project Densities with Spacing

Layout	Spacing (Diameters)	Density [MW/km^2] (4 MW Turbine)	Density [MW/km^2] (6 MW turbine)
L1	12	2.3	2.2
L2	10	3.4	3.2
L3	8	5.3	5.0

Figure 8-2 presents an example of a project layout with 10D spacing and 6 MW turbine model, resulting in an installed project density of 3.2 MW/km^2.

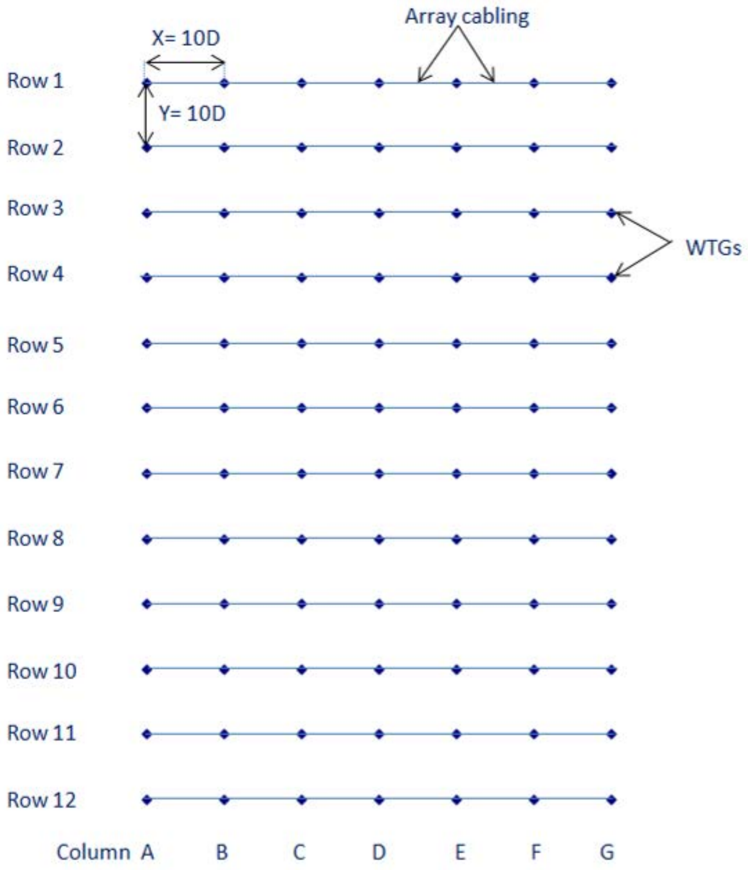


Figure 8-2: Example Project Layout for a 6 MW Turbine Option

8.4 Energy Calculations

GL GH WindFarmer (Version 4.2.2) software has been utilized to calculate the annual energy production for each project scenario (3 wind farm layouts × 2 turbine capacities), for each of the 24 wind climates previously described in Section 5. The GL GH Large Wind Farm Wake model has been employed as part of this analysis, to estimate the internal project wake losses. The energy production results for each scenario are summarized in Appendix B.

8.5 Net Capacity Factor Function Derivation

Based on the results of the above calculations, functions have been derived which allow the Net Capacity Factor (NCF), to be estimated as a function of turbine size, mean wind speed, and inter-turbine spacing (capacity density). The NCF provides a method for assessing the energy content of a given wind climate, which captures internal project wake losses. As the energy content of the wind climate and wake losses are averages across the generic project, the NCF can be considered applicable on a per-turbine basis. Figure 8-3 presents graph of NCF vs. project capacity, for the generic 4 MW turbine type and the three wind climates in the Atlantic North region.

Functions have been derived based on a two-stage function fitting exercise, as outlined below.

Stage 1

- Linear regression was used to derive a relationship between NCF and project density, for each turbine option and wind climate.
- The resulting linear function took the form:

$$NCF = (m \times Den) + c$$

Where: NCF = Net Capacity Factor [%]
Den = project Density (MW/km^2)
m = constant
c = constant

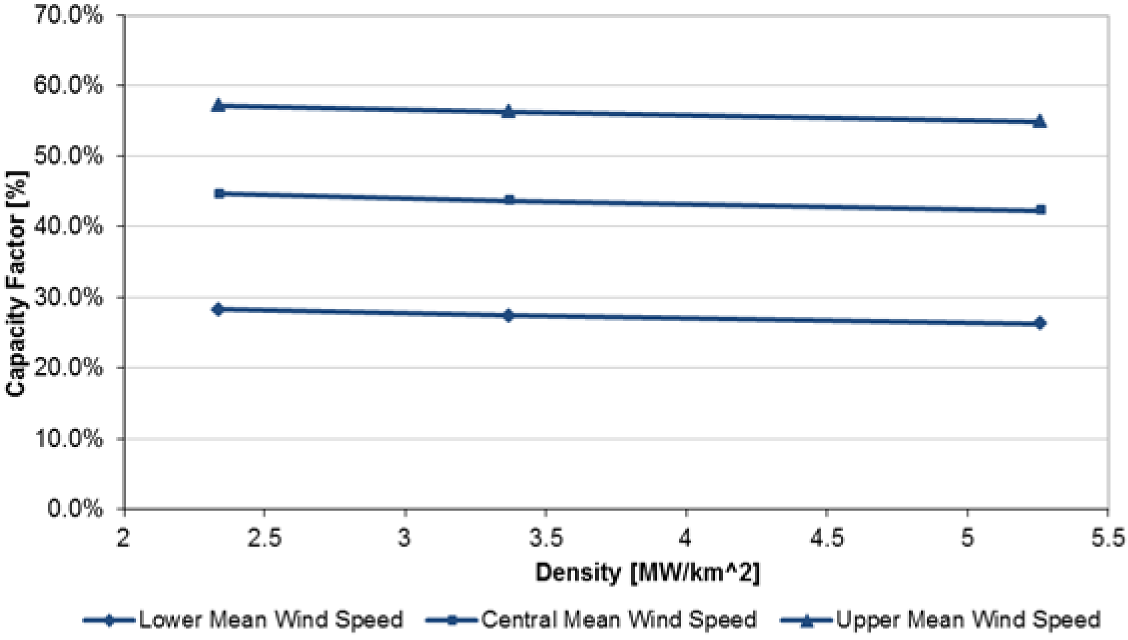


Figure 8-3: Net Capacity Factor (NCF) as a Function of Installed Density

Stage 2

- Second-order polynomials were used to derive a relationship between the above defined constants and wind speed.

The resulting functions, for each turbine option and wind climate, were integrated into their linear counterparts to derive a single function relating mean wind speed and capacity density to net capacity factor. The resulting NCF function and its respective coefficients per coastal region and for each turbine size are presented below.

$$NCF = (((A_1 \times MWS^2) - (A_2 \times MWS) + A_3) \times Den) + ((A_4 \times MWS^2) + (A_5 \times MWS) - A_6)$$

Where: *NCF = Net Capacity Factor [%]*
MWS = Mean wind Speed at hub height [m/s]
Den = Density [MW/km^2] (Note, this is not the wind farm cluster density)
$A_{1,2,3,4,\ldots6}$ *= Coefficients (zone and turbine specific)*

Table 8-3: NCF Function Coefficients per U.S. Coastal Region and Turbine Size

Coastal Region	Turbine Size [MW]	A_1	A_2	A_3	A_4	A_5	A_6
Atlantic North	4	2.1216E-04	3.7360E-03	8.5207E-03	-6.2818E-03	0.1864	0.6581
	6	2.3174E-04	3.9781E-03	9.0077E-03	-6.5923E-03	0.1914	0.6582
Atlantic Central	4	2.7426E-04	4.7415E-03	1.2309E-02	-6.3460E-03	0.1891	0.6723
	6	2.5689E-04	4.3402E-03	1.0132E-02	-6.9291E-03	0.1985	0.6892
Atlantic South	4	3.1400E-04	5.6116E-03	1.6327E-02	-5.7203E-03	0.1841	0.6735
	6	3.1358E-04	5.4805E-03	1.5153E-02	-6.5435E-03	0.1979	0.7084
Gulf of Mexico East	4	2.7754E-04	4.8507E-03	1.2890E-02	-6.1551E-03	0.1863	0.6629
	6	2.6183E-04	4.4683E-03	1.0753E-02	-6.7843E-03	0.1966	0.6832
Gulf of Mexico West	4	3.3597E-04	5.9238E-03	1.7023E-02	-6.1651E-03	0.1922	0.7057
	6	3.2184E-04	5.5313E-03	1.4617E-02	-6.9161E-03	0.2047	0.7338
Pacific South	4	2.8703E-04	4.6153E-03	1.0297E-02	-7.2637E-03	0.2001	0.6946
	6	2.4619E-04	3.8240E-03	6.5096E-03	-7.6405E-03	0.2054	0.6926
Pacific North	4	3.4870E-04	6.0812E-03	1.7930E-02	-5.3164E-03	0.1710	0.6013
	6	3.6883E-04	6.2668E-03	1.7852E-02	-6.2342E-03	0.1861	0.6421
Great Lakes	4	2.4255E-04	4.0476E-03	9.7028E-03	-5.8350E-03	0.1669	0.5386
	6	2.3363E-04	3.8378E-03	8.4960E-03	-6.3540E-03	0.1752	0.5534

8.6 Annual Energy Production Function

Annual energy production is derived by multiplying the NCF by the theoretical maximum energy output for a given single turbine unit or complete project. The theoretical maximum energy (TE) output for a given project size, is determined using the following function:

$$TE = CAP \times 8766 \times No.\ WTG\ Units$$

Where: *TE = Theoretical maximum energy [MWh/annum]*
CAP = Wind Turbine Rated Capacity [MW]
No. WTG Units = Number of turbines composing the project

Lastly, the Annual Energy Production (AEP) of any project under consideration is calculated using the following function:

$$AEP = TE \times NCF \times EXP \times COL \times AVAIL \times OTH$$

Where: *AEP = Annual Energy Production [MWh/annum]*
TE = Theoretical Maximum Energy [MWh/annum]
NCF = Net Capacity Factor [%]
EXP = Export System Efficiency [%] – (only applied for onshore grid connection)
COL = Collector System Efficiency [%]
AVAIL = Project Energy Availability [%] – derived in the O&M Analysis (Section 7)
OTH = Other Losses (blade degradation, high-wind hysteresis) [%]

9 LEVELIZED COST OF ENERGY

GL GH has considered the Levelized Production Cost (LPC) metric as the measure to compare offshore wind farm economics across U.S. waters.

The LPC is calculated as follows:

$$LPC = \frac{(CFCR \times Total\ CapEx) + (Total\ OpEx)}{AEP}$$

Where:

- LPC = Levelized Production Cost ($/MWh)
- Total CapEx = Capital Expenditure ($)
- CFCR = CapEx Fixed Charge Rate (%)
- Total OpEx = Operating Expenditure ($ / annum)
- AEP = Net Annual Energy Production (MWh / annum)

9.1 Capital Expenditure (CapEx)

Capital expenditure is derived by summing the overall results from the installation model and user inputs for other CapEx options, namely:

- Electrical Balance of Plant;
- Support Structure Design & Supply; and
- Wind Turbine Supply.

There are other large cost items that should be considered as part of the overall CapEx estimate, specifically;

- Project Development Costs [PDC] (assumed at 2.0% of CapEx);
- Project Management Costs [PMC] (assumed at 2.0% of CapEx);
- Construction Insurance [CI] (assumed at 1.0% of CapEx); and
- Legal & Financing Costs [LF] (assumed at 1.0% of CapEx).

GL GH considers it appropriate to consider the inclusion of a contingency which would be considered by developers as necessary to account for fluctuation in commodity prices as well as instability in the supply chain. It is anticipated that this contingency is simply represented by a percentage increase in the Total CapEx, and it is considered that the user shall have the flexibility to alter the magnitude of this increase. As a default assumption, GL GH has considered a contingency [CTG] of 10% of the Total CapEx, as detailed below:

$$Total\ CapEx = \begin{pmatrix} Support\ Structure\ CapEx + Installation\ CapEx + \\ Electrical\ System\ CapEx + Turbine\ Supply\ CapEx \end{pmatrix} \times PDC \times PMC \times CI \times LF \times CTG$$

9.2 Operational Expenditure (OpEx)

Operational expenditure is derived from the O&M OpEx Model.

9.3 Annual Energy Production (AEP)

Annual energy production is derived from the AEP Model. This value is taken directly into the LPC function.

9.4 Fixed Charge Rates

A Fixed Charge Rate [FCR] has been used to annualize capital expenditure taking account of project lifetime cash flows.

GL GH has included an assumed FCR of 12% in the model, though this can be varied by the user. This value is taken forward in the determination of Levelized Production Cost.

The following function can therefore be used to estimate the LPC:

$$LCoE = \frac{(0.12 \times CapEx) + (OpEx)}{AEP}$$

Where:

- LCoE = Levelized Cost of Energy ($/MWh)
- CapEx = Capital Expenditure ($)
- OpEx = Operating Expenditure ($ / annum)
- AEP = Net Annual Energy Production (MWh / annum)

10 RESULTS

The Installation and O&M LCoE Analysis Tool has been used to simulate the installation and operation of a generic 504 MW wind farm located off the U.S. Coast, allowing alternative wind farm installation methodologies and O&M strategies to be analyzed from a cost perspective. The wind farm installation aspect of the tool constitutes 47,712 alternative scenarios by assessing a wide range of installation methodologies across 24 alternative climatic conditions (see Section 5). The O&M aspect of the tool constitutes a further 462,240 scenarios in order to investigate the impacts of strategic decisions on O&M costs and availability. Further to the above, the tool provides the functionality for the user to amend all unit cost assumptions and key mobilization dates.

The results presented herein are taken directly from the Installation and O&M LCoE Analysis Tool and consider each of the eight regions modeled around the US Coast. From each of these regions, a total of 33 years of meteorological data have been sourced to determine the probabilistic weather delay with installation activities and central estimates of wind turbine access delay associated with O&M activities. The 33 years of metocean data are required to provide converged, long-term results for models containing stochastic elements indicative of the regions of interest.

The installation results presented in this section of the Report represent a P50 estimate of duration, and subsequent cost, considering the build duration of the 504 MW project as a whole. O&M results are central estimates of cost, assuming a 20-year project lifetime.

The Levelized Cost of Energy (LCoE) of a defined strategy depends on a combination of selected parameters:

- Climatic zone;
- Mean annual significant wave height (Hs);
- Project configuration;
- Distance to installation port;
- Distance to O&M port;
- Foundation installation methodology;
- Array cable installation methodology;
- WTG installation methodology;
- WTG reliability;
- O&M jack-up contracting strategy;
- O&M access strategy;
- Significant wave height (Hs) and speed limits of work boats; and
- Repair crew resource.

The number of parameters that can be independently varied means that the Installation and O&M LCoE Analysis Tool is capable of considering an extensive number of scenarios. Therefore, this section simply presents some key headline results which outline important sensitivities in terms of cost of energy, installation capital expenditure (CapEx), operational expenditure (OpEx), installation activity durations, and wind farm availability.

10.1 Assumed Base Case

In order to study the effect of sensitivity to variation in the above key inputs assumption, a single baseline case was defined as follows:

U.S. Region:	Atlantic Central
Mean Annual Significant Wave Height (Hs):	1.26 m
Wind Farm Configuration:	126 x 4 MW turbines
Distance to Installation Port:	75 Nm
Distance to O&M Port:	20 Nm
Foundation Installation:	Jacket – Pre-piled – Driven – Feeder Vessel
Array Cable Installation:	Jetting
Wind Turbine Installation:	Single Blade Installation
WTG Reliability:	Central
O&M Jack-up Contracting Strategy:	Open Market
O&M Jack-up Lead Time:	30 days
Work Boat Hs Capability:	1.25 m
Work Boats Speed:	20 knots

The above base-case is arbitrary and simply reflects a general approach to wind farm installation and operation. Installation activities assume the GL GH base case operations for driven, pre-piled jacket foundations, with the foundations transited to wind farm site using feeder barges (assuming three jacket foundations can be transported per trip). The model also assumes that wind turbines are installed utilizing a DP2 jack-up vessel (assuming 10 wind turbine units are transported per trip). The O&M strategy is optimized to identify the most economically advantageous access strategy and number of repair crews.

Figure 10-1 presents the resultant breakdown of CapEx for the baseline case.

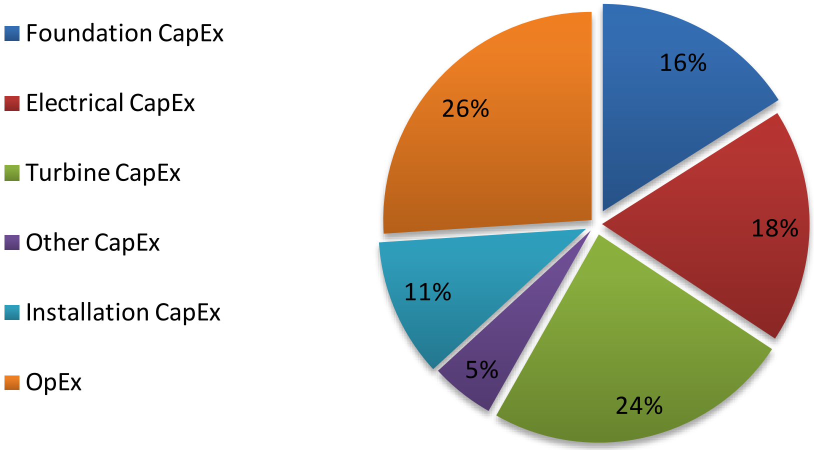


Figure 10-1: Total Wind Farm Costs for Full Lifetime

Further breakdowns of CapEx and specifically installation costs are presented in Figure 10-2 and Figure 10-3, respectively.

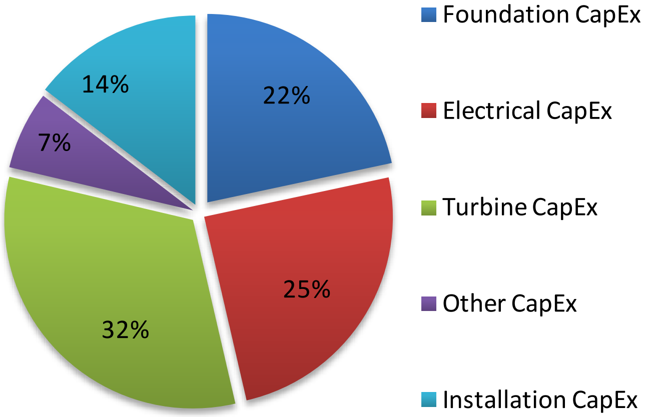


Figure 10-2: CapEx Breakdown

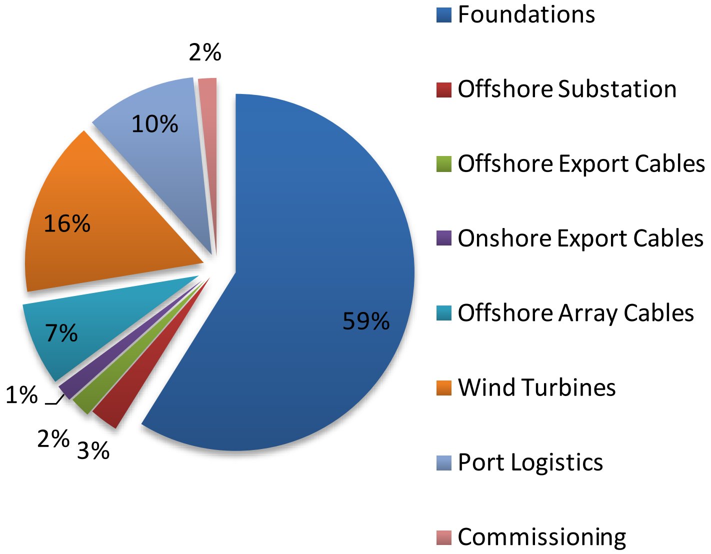


Figure 10-3: Installation Costs Breakdown

Figure 10-4 presents a breakdown of the project's completed OpEx budget. It should be noted that the breakdown includes aspects of project OpEx which are not specific to the access methodology employed on the project, such as way-leaves, insurance, etc.

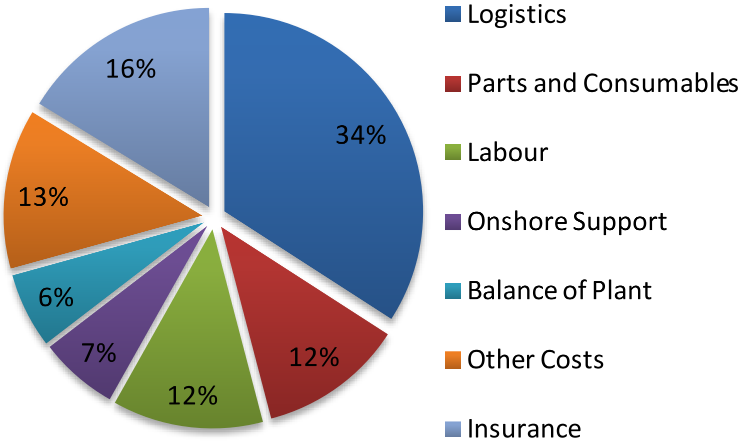


Figure 10-4: OpEx Breakdown

10.2 Key Sensitivities to LCoE

A series of model runs were conducted in order to investigate the impact of variations in wind climate, distance to port, project configuration (size and resultant number of wind turbines), foundation installation methodology and O&M access strategy. It should be noted that the O&M access strategy and repair resource (see Section 7.2.1) have been optimized by seeking to minimize the sum of direct costs and lost production cost (see Section 7.2.1) for each sensitivity analysis below unless stated otherwise. The results of these analyses are detailed in the following sub-sections.

10.2.1 Sensitivities to Variations within Climatic Zone

The impact of varying the severity of climate within the same climatic zone has been assessed. In order to test the sensitivity of the results to changes in regional climate severity, the base case assumptions have all been kept constant, while varying the severity of the metocean climate. The mean Hs (and associated wind climate) within the Atlantic Central zone was varied according to the values specified in Table 10-1, as well as the overall project LCoE for each scenario. It must be noted that all installation assumptions have been kept constant, however, in order to assess the lowest LCoE for each climatic zone the O&M strategy has been optimized as detailed in the Table 10-1.

Table 10-1: Levelized Cost of Energy within Climatic Zone

Climate	O&M Strategy	Mean Hs [m]	LCoE [$/MWh]
Atlantic Central Benign	Port based Work boats (12 sched. crews + 15 repair crews, 2 sched. Vessels + 2 repair Vessels)	0.59	179
Atlantic Central Moderate (Base Case)	Work boats + Helicopter support (17 sched. crews + 15 repair crews, 2 sched. vessels + 2 repair vessels)	1.26	193
Atlantic Central Onerous	Work boats + Helicopter support (27 sched. crews + 22 repair crews, 3 sched. Vessels + 3 repair Vessels)	1.93	235

Figure 10-5 presents durations for all key installation activities. The length of each bar presents the total time taken in days, with varying colors to demonstrate a further breakdown in total duration, attributable to weather and logistic/vessel delays (Section 6.2.5).

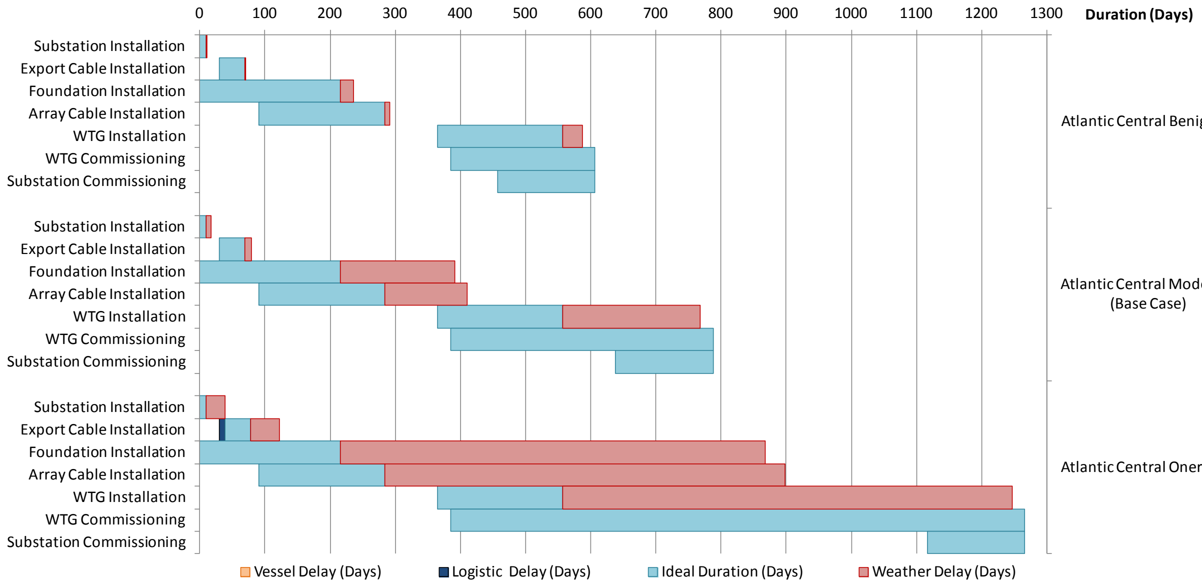


Figure 10-5: Installation Durations within Climatic Zone

Naturally, as demonstrated in Figure 10-5, weather delay increases with climate severity for the same set of installation and vessel assumptions. Harsher climates result in less frequent weather windows where metocean conditions are within installation limits, thus resulting in further delays. Logistics delays occur when a vessel has been mobilized, but is waiting for a previous dependent activity to finish before it can commence. Logistic delay is heavily dependent on the project program which dictates when specific vessels are mobilized. The installation project program presented above has been optimized for the base case scenario; therefore, logistic delays could be reduced for alternative scenarios by adjusting the mobilization dates of vessels to better account for the likely total durations for other aspects of the installation program. The effects of this are particularly apparent as the climate becomes more onerous as operations commence significantly later than their corresponding vessel mobilization dates.

Figure 10-7 presents O&M direct costs and corresponding project availability for the above case. Access strategy and number of repair crews were determined by optimizing in terms of total O&M cost, the sum of direct costs and lost-production costs (Section 7.2).

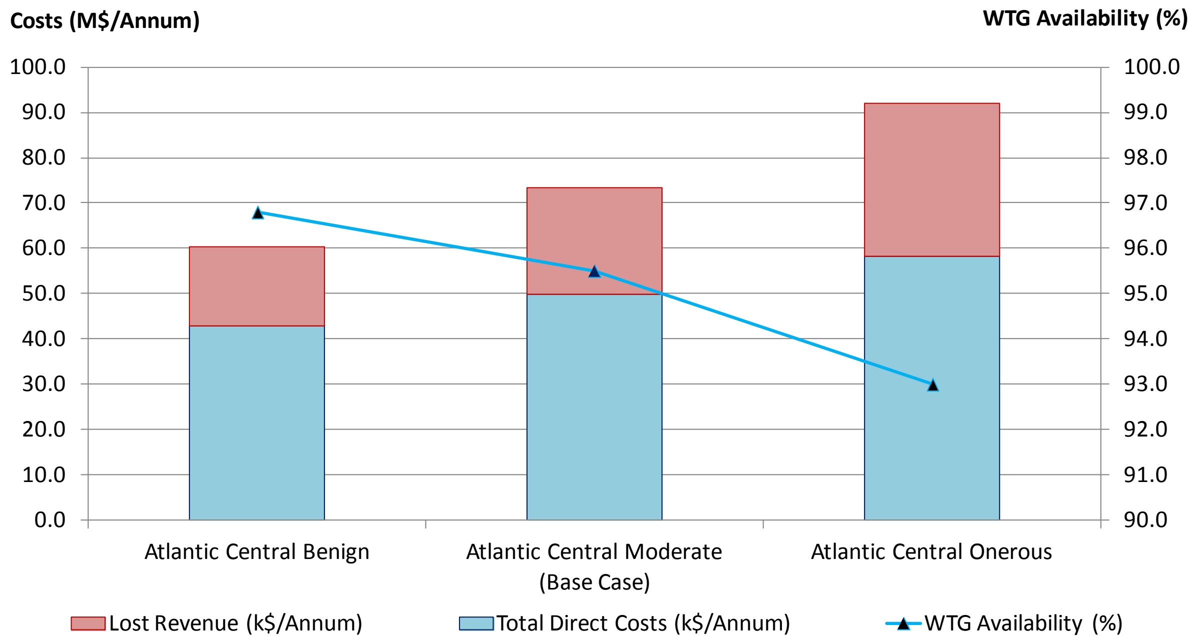


Figure 10-6: O&M Costs and WTG Availability within Climatic Zone

Despite the re-optimization of O&M resourcing for each climate state, the increase in spending on resource is insufficient to alleviate the reduced availability and lost production costs incurred by the harsher conditions. This is a result of the restricted access to wind turbines as the metocean conditions more frequently exceed the operational limits of the O&M vessels.

Figure 10-7 presents LCoE, considering Installation CapEx and project OpEx only (the development, design, supply, and management costs are not shown). It is clear that installation CapEx and project OpEx increase non-linearly with more onerous climates, as metocean conditions exceed operation weather limitations more frequently, resulting in further weather delay and higher vessel expenditure. Of note is the contribution of installation CapEx and project OpEx to the overall project LCoE when varying climate severity.

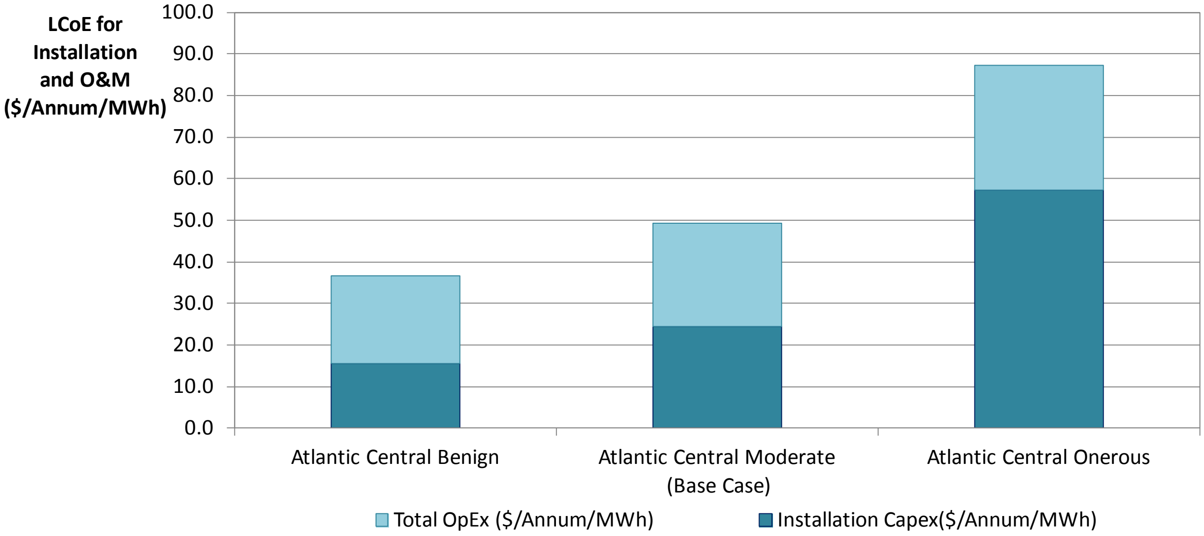


Figure 10-7: Levelized Cost of Energy for Installation and O&M within Climatic Zone

For the case presented above, it can be seen that moving from a benign to an onerous climate increases the contribution of installation CapEx and O&M costs to total LCoE, from 42% and 58% respectively to 66% and 34%. However, it should be noted that this increase may not be as large in real-life situations, where delays may impact delivery schedules, payment milestones, storage and other contractual matters, resulting in increases in capital expenditure on other aspects of the project, which have not been considered herein.

Overall, this sensitivity analysis shows that an increase in climatic severity can significantly impact project LCoE.

10.2.2 Sensitivities to Variation in Metocean Climate between Climatic Zones

The impact of varying climatic zone has been assessed to test the sensitivity of the costs to changes in US regions. As above, all base case installation assumptions, except selected climate zone, have been kept constant. However, in order to obtain the minimum LCoE in each Climatic Zone, the O&M strategy has been optimized for each of them. For the installation logistics, the only variable considered is the change in mean significant wave height (Hs) and change in exceedance/persistence trends associated with the sea-states within each region.

Table 10-2 presents the mean Hs values, the optimized O&M strategy and the overall project LCoE corresponding to each climatic zone.

Figure 10-8 presents durations for all key installation activities, for each of the climatic regions, excluding the two Pacific regions which are presented in Figure 10-9. As above, the length of each bar presents the total time taken in days, with colors demonstrating a further breakdown in total duration attributable to weather and logistic/vessel delays (Section 6.2.5).

Table 10-2: Levelized Cost of Energy with Varying Climatic Zone

Climate	O&M Strategy	Mean Hs [m]	LCoE [$/MWh]
Atlantic Central Moderate (Base Case)	Work boats + Helicopter support (17 sched. crews + 15 repair crews, 2 sched. vessels + 2 repair vessels)	1.26	193
Atlantic North Moderate	Work boats + Helicopter support (15 sched. crews + 15 repair crews, 1 sched. vessels + 2 repair vessels)	1.26	192
Atlantic South Moderate	Work boats + Helicopter support (17 sched. crews + 15 repair crews, 2 sched. vessels + 2 repair vessels)	1.26	184
Gulf of Mexico East Moderate	Work boats + Helicopter support (15 sched. crews + 15 repair crews, 1 sched. vessels + 2 repair vessels)	1.23	190
Gulf of Mexico West Moderate	Work boats + Helicopter support (15 sched. crews + 15 repair crews, 2 sched. vessels + 2 repair vessels)	1.23	186
Great Lakes Moderate	Work boats + Hovercraft support (12 sched. crews + 15 repair crews, 1 sched. vessels + 2 repair vessels)	0.73	199
Pacific South Moderate	Work boats + Helicopter support (89 sched. crews + 27 repair crews, 9 sched. vessels + 3 repair vessels)	2.25	974
Pacific North Moderate	Work boats + Helicopter support (35 sched. crews + 27 repair crews, 4 sched. vessels + 3 repair vessels)	2.25	665

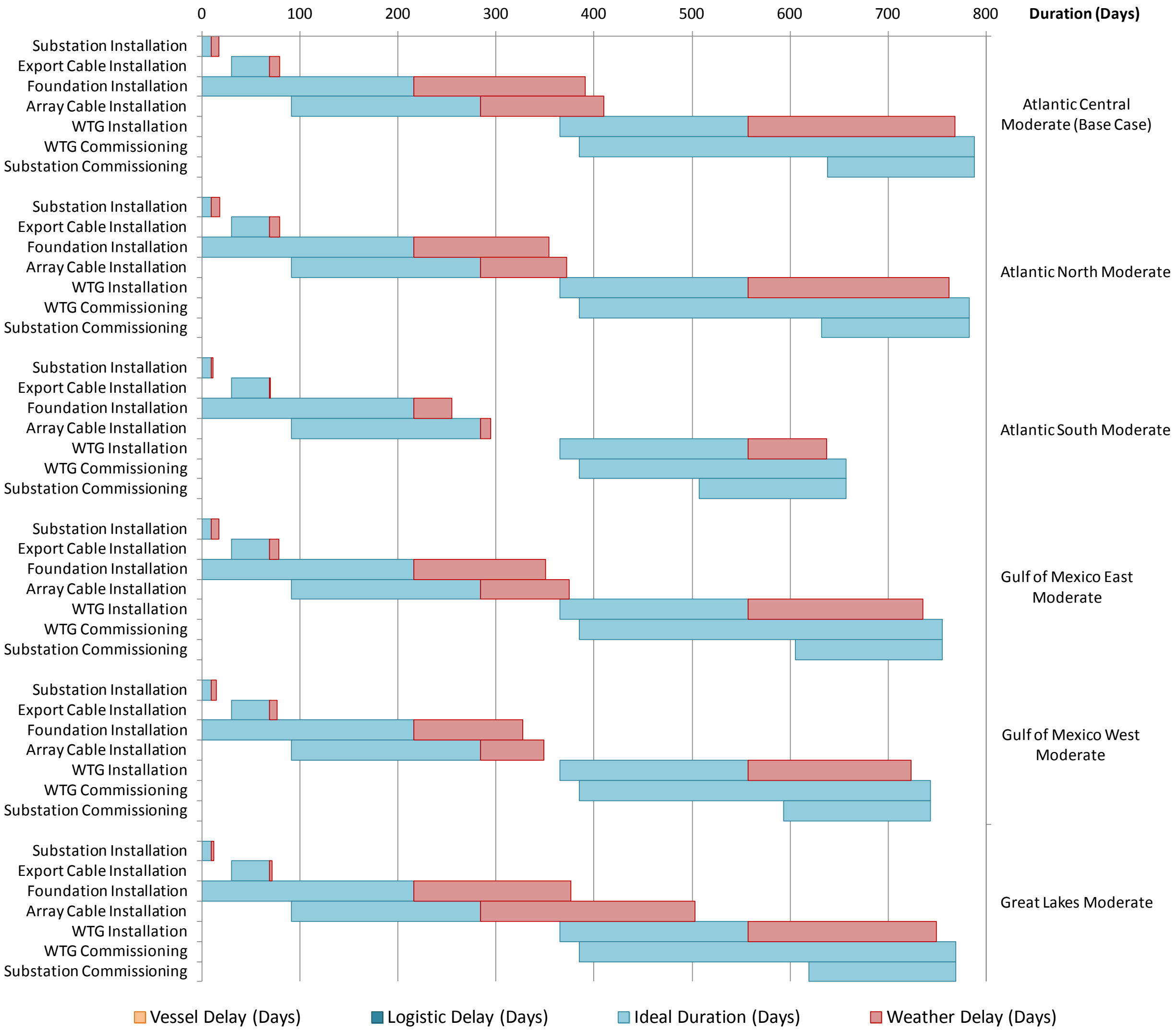


Figure 10-8: Installation Durations with Varying Climatic Zone (excludes Pacific regions)

Given the same strategic assumptions, the ideal activity durations remain constant throughout the zones, with weather delay varying as a function of climate severity. It should be noted that the project programs have been optimized with a view to reducing logistic and vessel delays.

Figure 10-9 presents the installation durations for the Pacific Coast regions, which are presented on an alternative scale, due to the severity of these climates and the impact on durations.

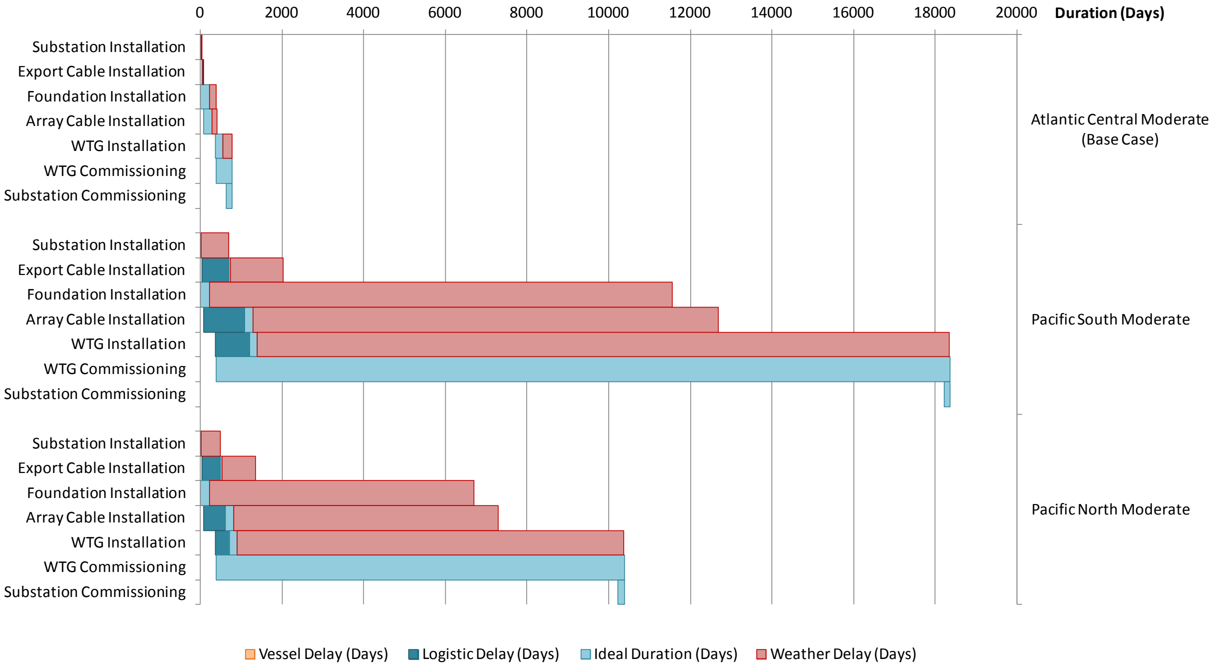


Figure 10-9: Installation Durations with Varying Climatic Zone for Pacific regions

The results demonstrate the dramatic impact of the onerous metocean conditions found in the Pacific region, with the ideal duration values insignificant compared to weather and logistic delays. This demonstrates the difficulty in finding weather windows wherein conditions are below offshore installation activity limits. Clearly GL GH's baseline operation methodology and limitations, representing common installation methods, are not realistic in climates of this severity; therefore alternative solutions will be necessary in order to build in these climates. Based on the results presented here, the project program could be optimized further, by accounting for weather delays when scheduling vessel mobilization dates. This would have the beneficial impact of minimizing project logistic delays.

Figure 10-10 presents O&M direct costs and corresponding project availability for the above case. Again, results for the two Pacific regions are shown separately in Figure 10-11 due to the significantly larger costs associated with O&M in these two regions.

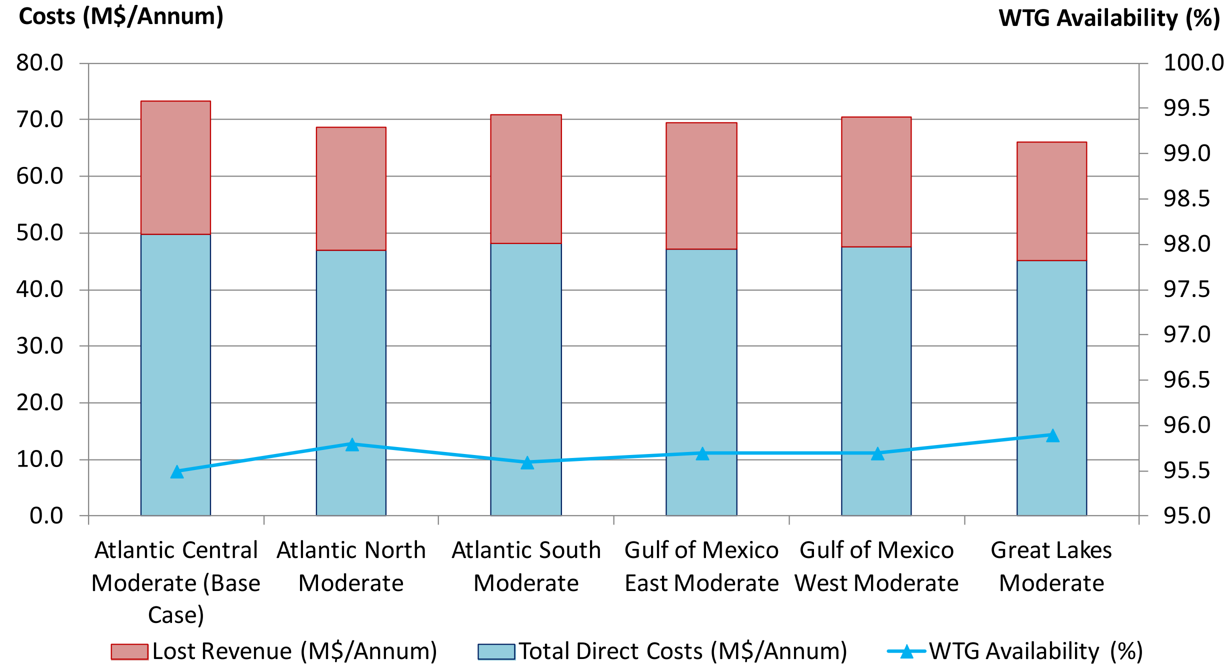


Figure 10-10: O&M Costs and WTG Availability with Varying Climatic Zone

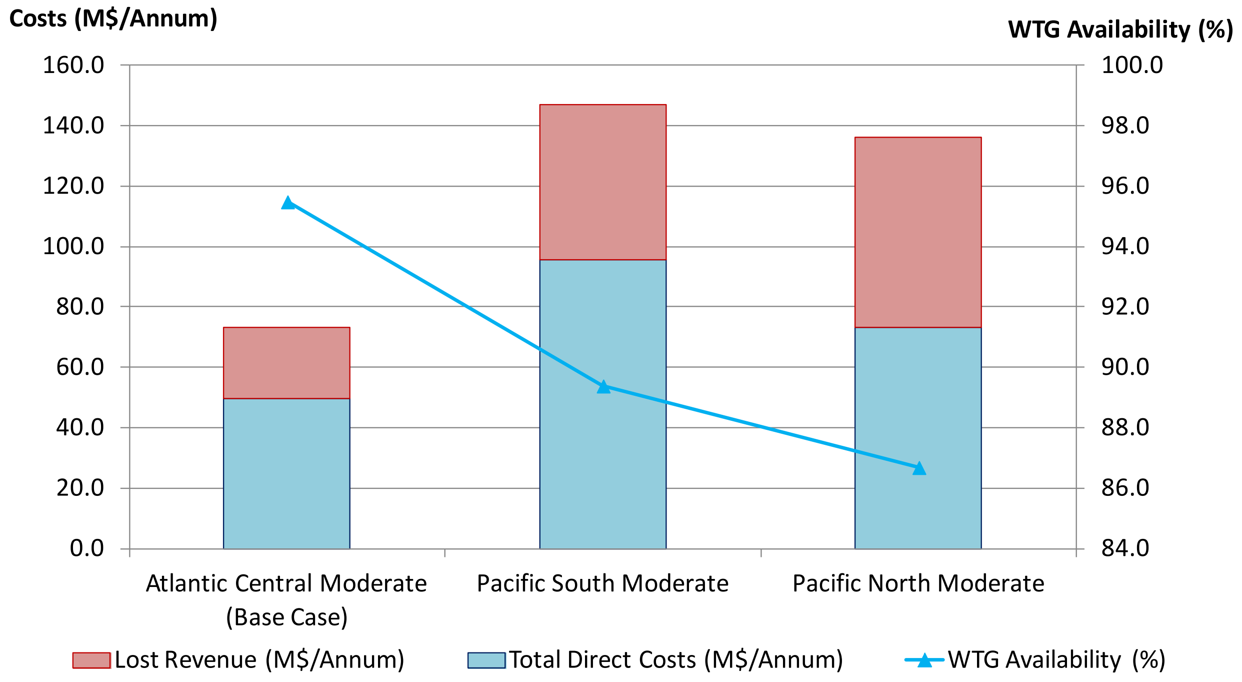


Figure 10-11: O&M Costs and WTG Availability with Varying Climatic Zone

As previously, O&M strategy and resourcing was determined by seeking to minimize the sum of direct costs and lost-production costs (see Section 7.2). It can be seen from Figure 10-10 that high project availability can be achieved in the majority of regions with OpEx values of around $50M per annum. However, Figure 10-11 shows that the harsh climatic conditions within the Pacific regions can seriously impact project availability and O&M costs given the assumptions made in this case. Projects in these regions are likely to be reliant on larger, more expensive vessels and helicopters to access the wind turbines.

Figure 10-12 presents LCoE for each of the regions, considering Installation CapEx and project OpEx only. Again, the Pacific regions are omitted and presented separately in Figure 10-13 due to the substantial difference in scale.

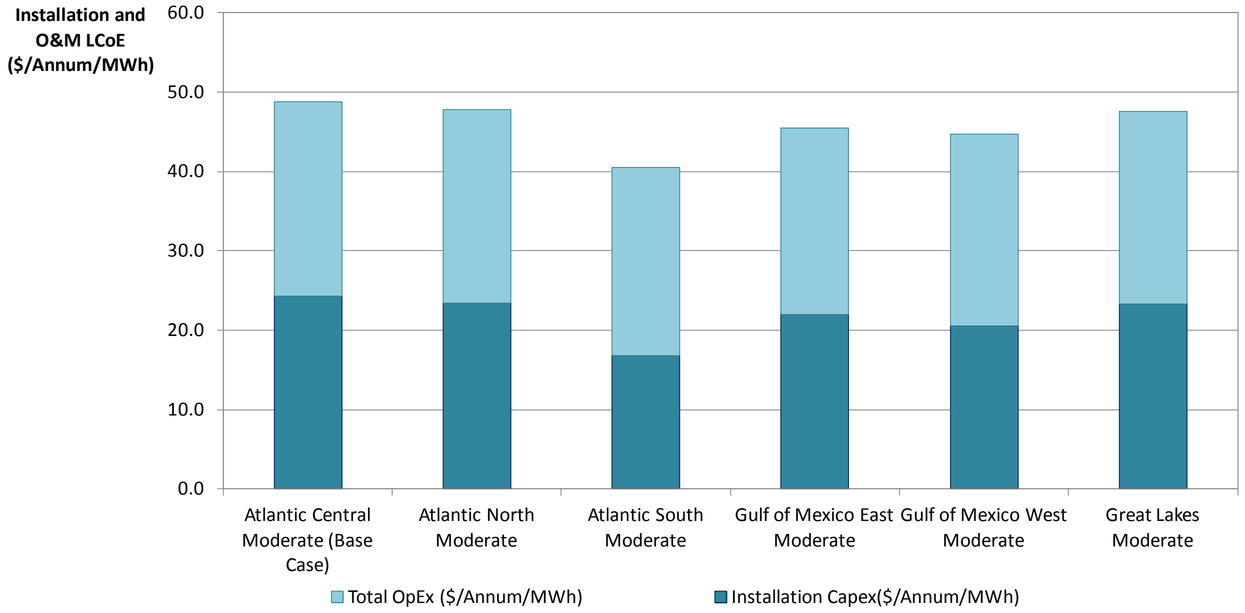


Figure 10-12: Levelized Cost of Energy for Installation and O&M with Varying Climatic Zone

As expected, installation CapEx and project OpEx increase with the more severe regional metocean climates, where conditions exceed operation weather limitations more frequently, resulting in further weather delay and higher vessel expenditure. Of note is the variation in Levelized costs for Levelized modeled Atlantic regions, which share the same mean significant wave height. The reason for this is in the exceedance/persistence of the sea-states, with the southern region having access to a greater frequency of longer weather-windows of relatively benign weather.

Another point of note is the higher costs associated with the Great Lakes Region, which has the lowest mean Hs of all regions. This is a direct result of the occurrence of sea-ice reducing the period available for installation activities. It should be noted that GL GH has assumed that vessels remain active during icing periods (i.e. a cost to the project). The main reason for this is the unpredictable nature of the sea ice, which may preclude the planning of demobilization and remobilization during winter months. The isolated nature of the Great lakes will also make it more difficult for specialist installation vessels to move to other projects in other regions during these periods, given the limited access to the Lakes.

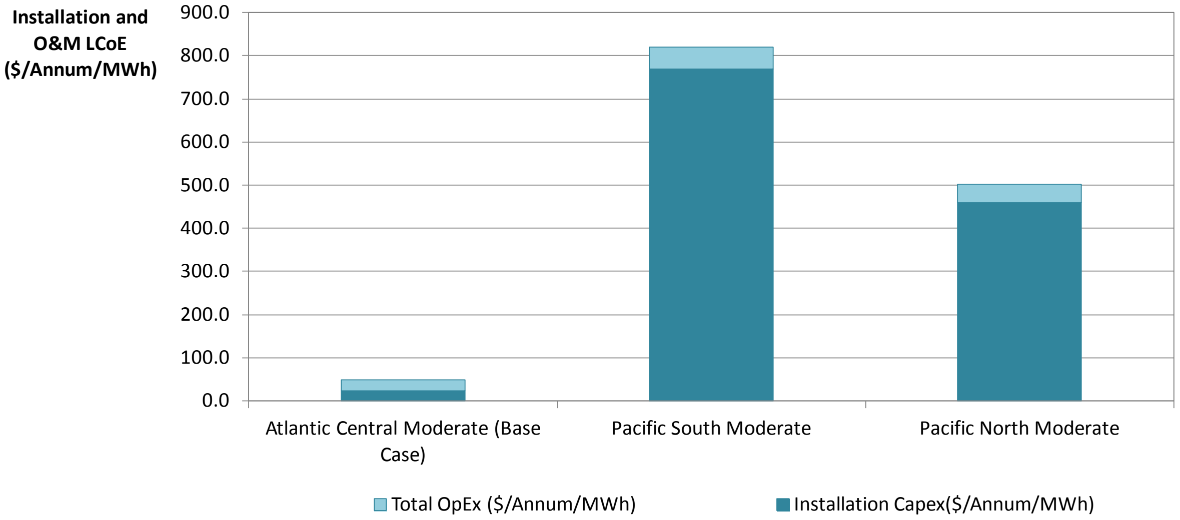


Figure 10-13: Levelized Cost of Energy for Installation and O&M with Varying Climatic Zone

Figure 10-13 demonstrates that, for the Pacific regions, by far the greatest influence to LCoE is installation CapEx. The LCoE Analysis Tool requires that installation weather windows are continuous, and this requirement is most difficult to fulfill in the Pacific. While project O&M costs are also greater than for the other regions, they are a minor contributor to the LCoE costs in the Pacific regions. This is likely due to the reduced requirement for sustained, long weather windows for wind turbine O&M works as well as the pre-optimization applied under this analysis, allowing the model to adopt more capable vessels and helicopters in a bid to mitigate the severe metocean climate.

10.2.3 Sensitivity to Variation of Distances to Ports

GL GH has investigated the impact of varying the distance from the wind farm project to the installation mobilization port and the O&M logistics port and associated parts store. To test the sensitivity of the LCoE results to changes in distance to port, the base case assumptions have been kept constant with only vessel transit times being varied. As previously, in order to present the lowest LCoE for each scenario, O&M strategy and resourcing were determined by seeking to minimize the sum of direct costs and lost-production costs. Table 10-3 presents the distances to installation and O&M ports analyzed, the O&M strategy considered along with the corresponding overall project LCoE for each scenario.

Table 10-3: Levelized Cost of Energy with Varying Distances to Ports

Climate	Distance to Installation Port [Nm]	Distance to O&M Port [Nm]	O&M Strategy	LCoE [$/MWh]
Atlantic Central Moderate	25	10	Work boats + Helicopter support (15 sched. crews + 15 repair crews, 1 sched. vessels + 2 repair vessels)	190
Atlantic Central Moderate (Base Case)	75	20	Work boats + Helicopter support (17 sched. crews + 15 repair crews, 2 sched. vessels + 2 repair vessels)	193
Atlantic Central Moderate	150	70	Offshore base with work boats access (15 sched. crews + 15 repair crews, 1 sched. vessel + 2 repair vessels)	207

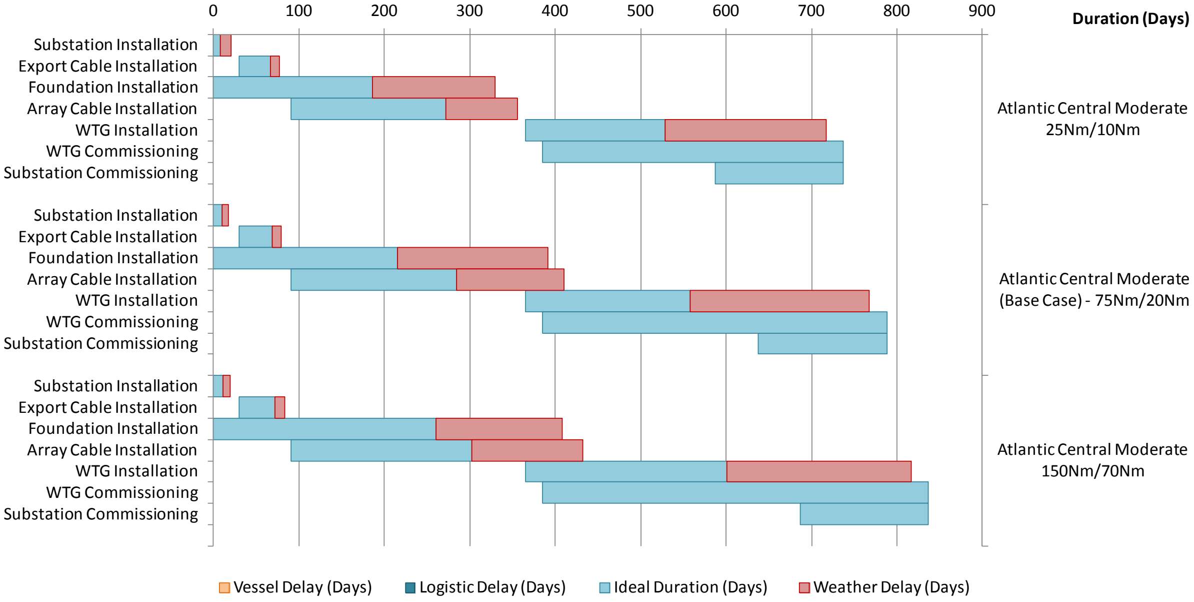


Figure 10-14: Installation Durations with Varying Distances to Ports

Figure 10-14 presents durations for all key installation activities for each of the distances between the wind farm project site and the installation staging port and O&M port. It can be seen that ideal duration varies slightly due to the variation of distance to port, as the vessel transit time is affected. This has a knock-on impact on weather delay, due to a larger weather window being required for vessel transit to the project site.

Figure 10-15 presents O&M direct costs and corresponding project availability for the above case. Of note is the high increase in direct costs and WTG availability when moving from 20 Nm to 70 Nm from the O&M Port. In this scenario, an Offshore Based personnel Strategy increases the total O&M costs, but provides improved accessibility through reduced transit times, thereby limiting lost production costs. For projects closer to the O&M Port, the cost of an offshore base or a floatel strategy becomes less attractive as the advantages of being located close to the project site are reduced and therefore optimization has selected helicopter support as a more appropriate strategy.

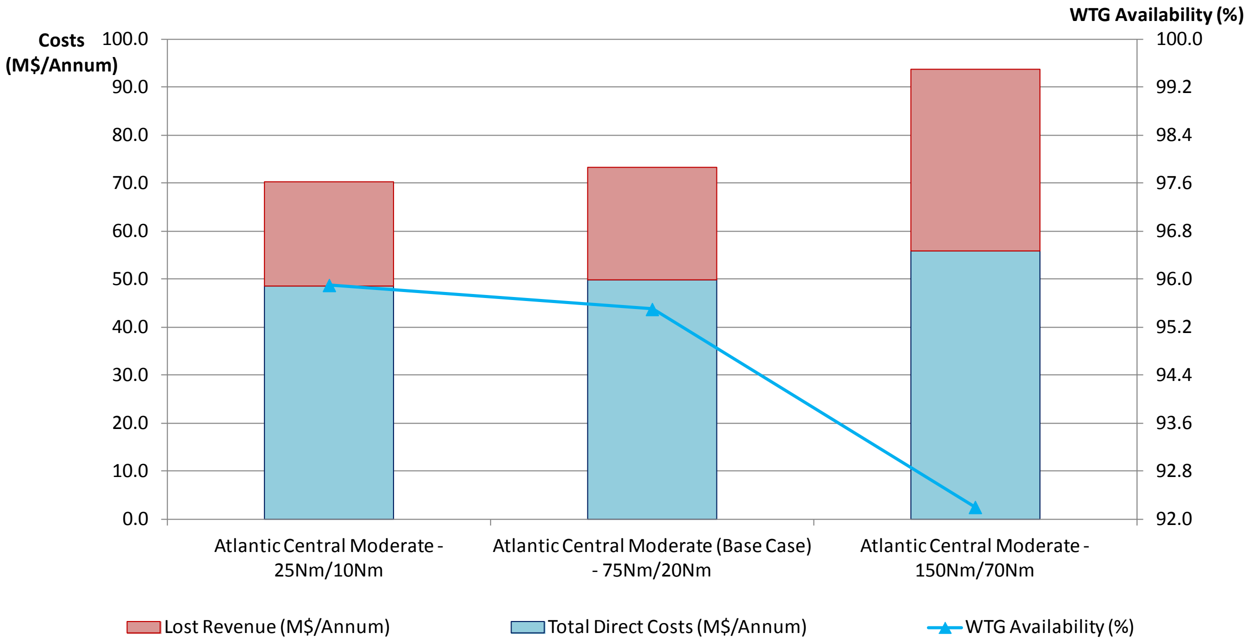


Figure 10-15: O&M Costs and WTG Availability with Varying Distances to Ports

Figure 10-16 presents the Installation CapEx and OpEx LCoE for each of the modeled distances between the wind farm project site and the installation staging port and O&M port. Of note is the greater sensitivity that the O&M costs have to changes in distance. This is as a result of the increased transit times as well as the strategic shift to the more expensive, offshore-based strategy. In the case presented here, installation costs are less sensitive to distance, given the use of feeder vessels to transport foundations to the wind farm site, which allows for time savings compared to using the installation vessel as the transport medium.

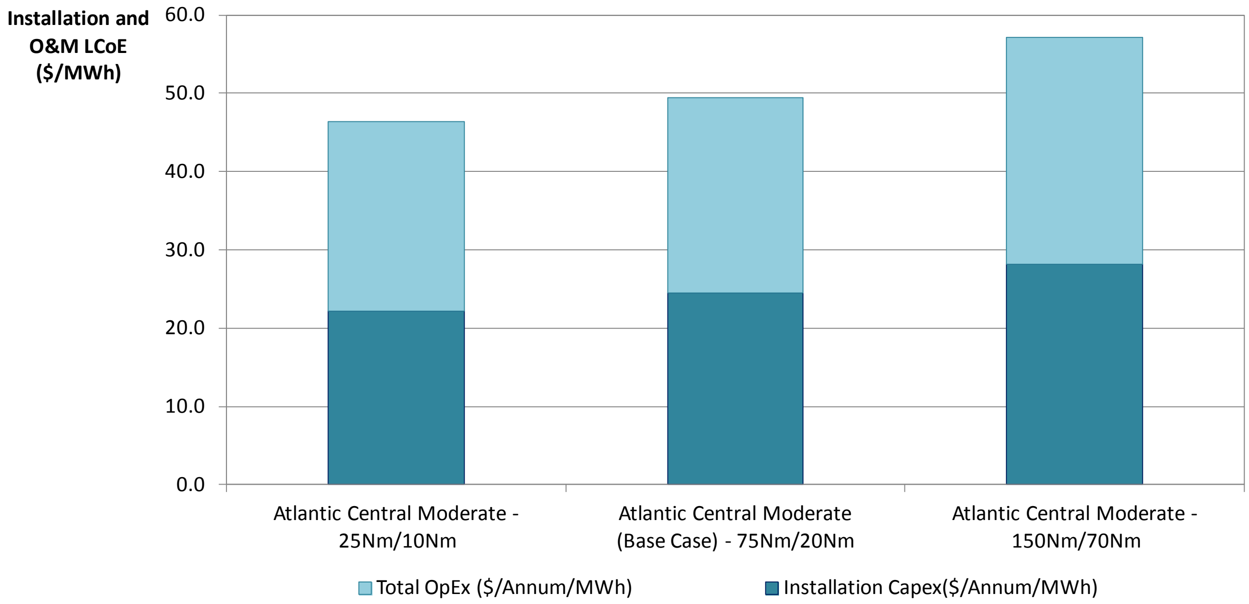


Figure 10-16: Levelized Cost of Energy for Installation and O&M with Varying Distances to Ports

10.2.4 Sensitivity to Variation of Project Configuration

GL GH has investigated the impact of varying project configuration on the costs associated with installation and O&M. The aim is to assess how these costs are influenced by fewer, larger wind turbines. In order to test this sensitivity, GL GH has retained the base case assumptions, while varying the number and capacity of the WTGs, as presented in Table 10-4. Also in Table 10-4 are the overall project LCoE results associated with each configuration. As previously, in order to present the lowest LCoE for each scenario, O&M strategy and resourcing were determined by seeking to minimize the sum of direct costs and lost-production costs.

Table 10-4: Levelized Cost of Energy with Varying Project Configuration

Climate	O&M Strategy	Project Configuration	LCoE [$/MWh]
Atlantic Central Moderate (Base Case)	Work boats + Helicopter support (17 sched. crews + 15 repair crews, 2 sched. vessels + 2 repair vessels)	126 x 4 MW	193
Atlantic Central Moderate	Work boats + Helicopter support (15 sched. crews + 15 repair crews, 1 sched. vessels + 2 repair vessels)	84 x 6 MW	166

Figure 10-17 presents durations for all key installation activities, for both scenarios considered. The modeling suggests that there are substantial benefits to be gained, in terms of installation timings and subsequent weather downtime, by opting for fewer, larger wind turbines. This is not unexpected, as the ideal duration to install a 6 MW wind turbine, and its associated balance of plant, is not considered to be as much as 1.5 times the duration for a 4 MW wind turbine. It is therefore possible to take advantage of the economies of scale when installing larger wind turbines. Likewise it is considered that capacity alone need not impact on turbine reliability and hence no discrimination has been applied here in terms of reliability with varying turbine capacity.

It should be noted that the 6 MW wind turbine project configuration presented in Figure 10-17 was not optimized in terms of vessel mobilization dates. As such, there is more float built into the project program than necessary. Further optimization of the project program would therefore result in greater savings.

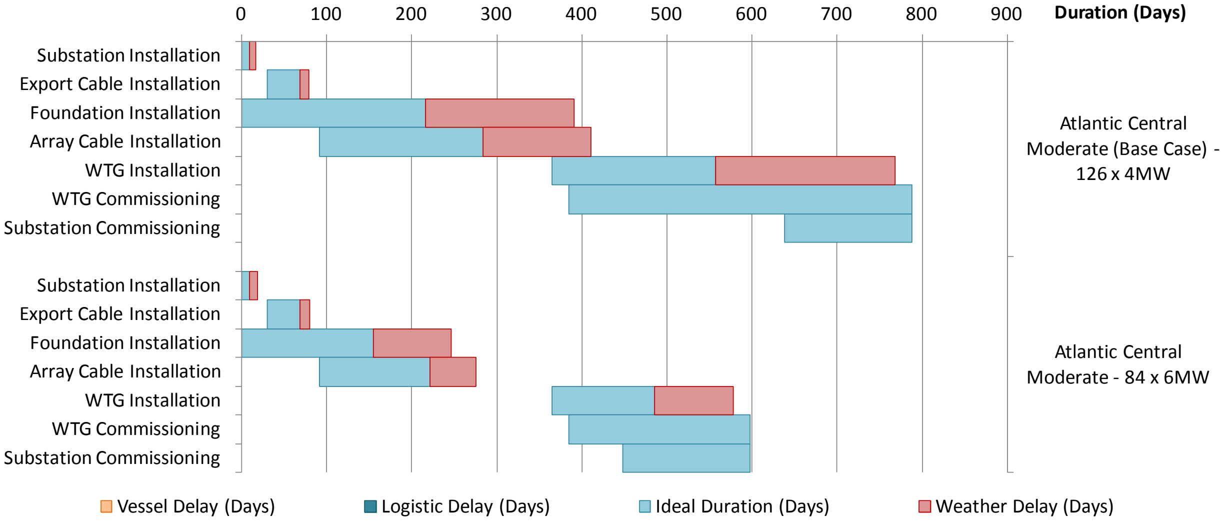


Figure 10-17: Installation Durations with Varying Project Configuration

Figure 10-18 presents O&M direct costs and corresponding project availability for the above case. It can be seen that there is a minor decrease in wind farm availability when moving to a larger wind turbine. It should be noted that this is not a direct result of the wind turbine technology, as GL GH has assumed the same wind turbine reliability statistics for both wind turbine sizes; rather, it is a direct result of optimizing O&M access strategy for each scenario, therefore better allocating available resource to repair wind turbines.

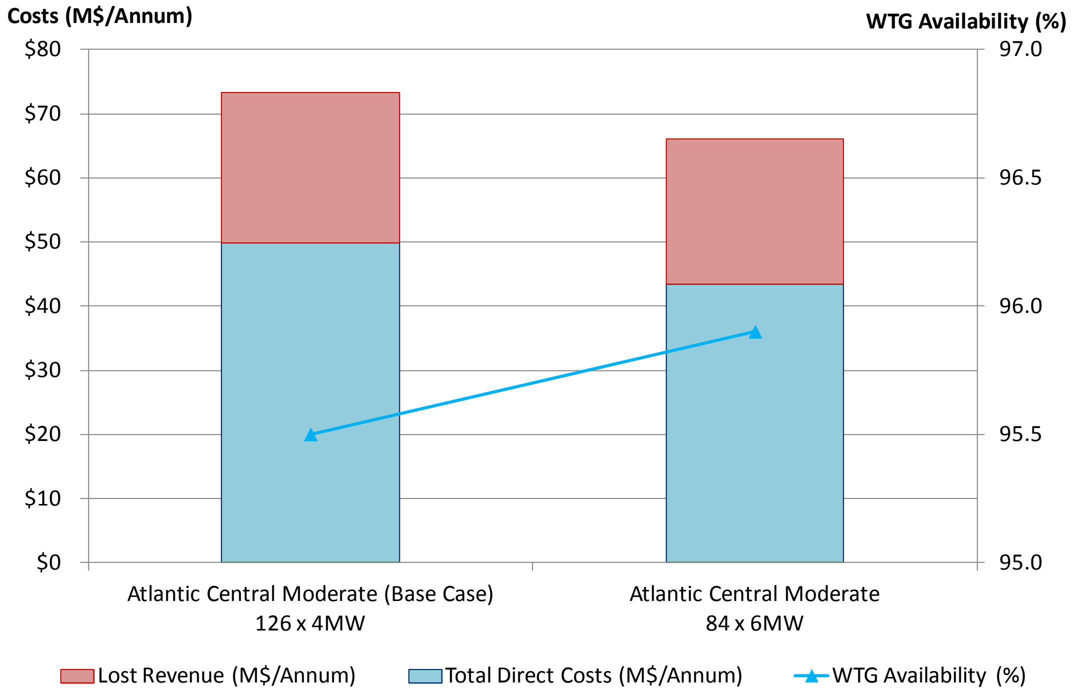


Figure 10-18: O&M Costs and WTG Availability with Varying Project Configuration

Figure 10-19 presents the LCoE for each of the configurations, considering Installation CapEx and project OpEx only. It can be seen that significant cost savings can be achieved through the installation of fewer, larger wind turbines. It should, however, be noted that the 6 MW wind farm configuration has an energy capacity factor of 47.8%, compared to 45.7% for the 4 MW configuration. LCoE is therefore also impacted by estimated energy production as well as CapEx and OpEx values.

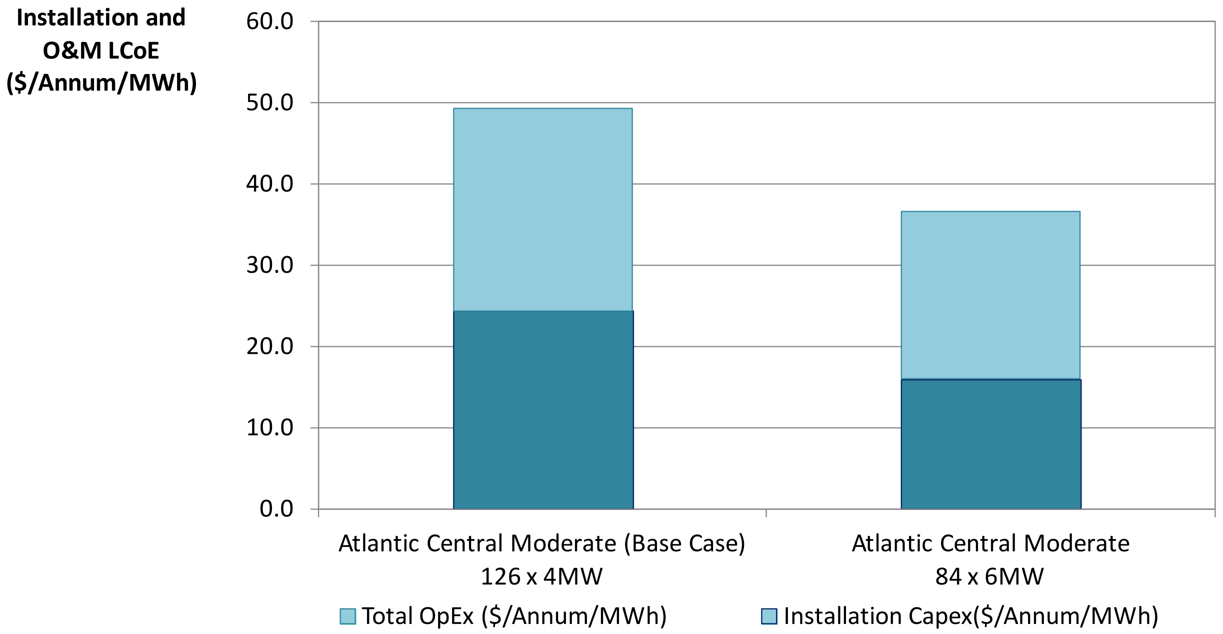


Figure 10-19: Levelized Cost of Energy for Installation and O&M with Varying Project Configuration

10.2.5 Sensitivity to Variation of Foundation Installation Methodology

GL GH has investigated the influence of foundation installation methodology on installation duration and costs. As with all the scenarios assessed above, GL GH has maintained all base case assumptions and since the type of foundation doesn't affect the O&M strategy, this has also been kept constant, with foundation installation methodology being the only variable considered.

A range of foundation concepts has been selected for modeling in an attempt to demonstrate the range of possible methodologies included as default within the Installation and O&M LCoE Analysis Tool. The selected concepts are presented in Table 10-5 along with the corresponding overall project LCoE results for each scenario.

Table 10-5: Levelized Cost of Energy with Varying Foundation Installation Methodology

Climate	Foundation Installation Methodology	LCoE [$/MWh]
Atlantic Central Moderate	Monopile - driven - feeder vessel	176
Atlantic Central Moderate	Jacket - pre-piled - driven - installation vessel	190
Atlantic Central Moderate (Base Case)	Jacket - pre-piled - driven - feeder vessel	193
Atlantic Central Moderate	Jacket - post-piled - driven - feeder vessel	196
Atlantic Central Moderate	GBS with full turbine concept	205
Atlantic Central Moderate	GBS - feeder vessel	208

Figure 10-20 presents durations for all key installation activities, for both scenarios considered. All the installation programs assume that the installation of wind turbines take place 1 year after the start of the foundations installation activities and could be optimized to avoid any float time in the program. Of note is the comparison between the three jacket installation methodologies, with the post-piled jackets appearing to take longer than pre-piled equivalent (base case). This suggests that utilizing separate installation vessels for pin-piles and jacket lattice structures benefits the project. This comparison also suggests that, for the 75Nm transit distance from port assumed here, using the installation vessel to collect the foundation components provides a shorter project schedule.

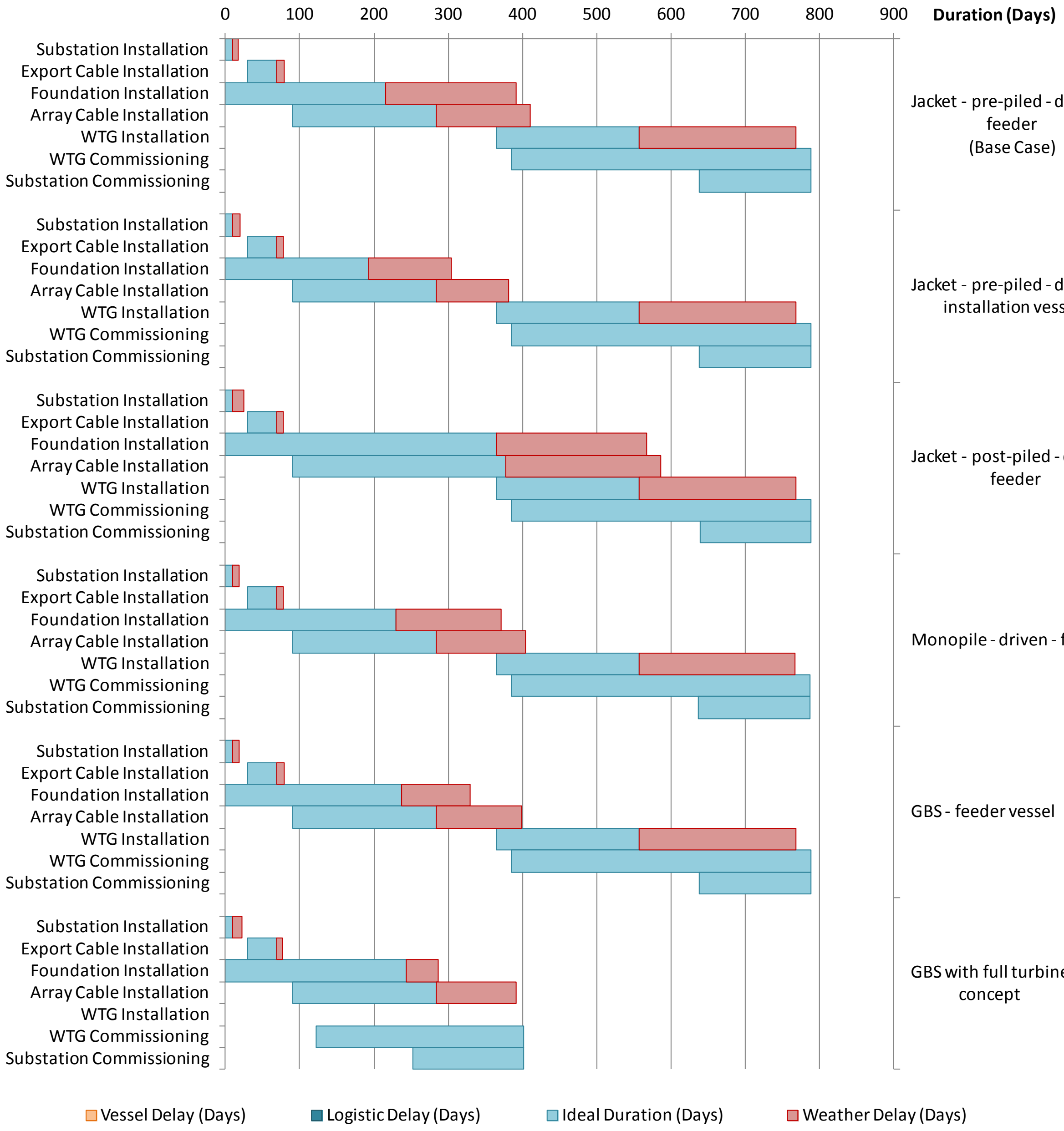


Figure 10-20: Installation Durations with Varying Installation Methodology

The ‘GBS with full turbine’ installation and the pre-piled jackets using the installation vessel as transportation vessel are the quickest of all the foundation concepts to install; however, in the case of the GBS foundations there are significant lead-times and costs which aren’t captured within the model and which are typically associated to the manufacture of these structures. Note that the ‘GBS with full turbine’ methodology does not consider a separate wind turbine installation activity, as the wind turbine is installed with the foundation in a single pass.

Figure 10-21 presents the LCoE for each of the installation methodologies, with a breakdown provided for each activity to reflect interdependencies between the foundation installation and the installation of other plant. As can be seen in Figure 10-21, foundation installation accounts for a substantial portion of the total installation cost of an offshore project, followed by wind turbines. However, it should be noted that the durations used to inform these costs are representative of the 504 MW generic project under consideration as part of this study, and therefore these durations and costs should not be viewed as absolute for all offshore wind projects.

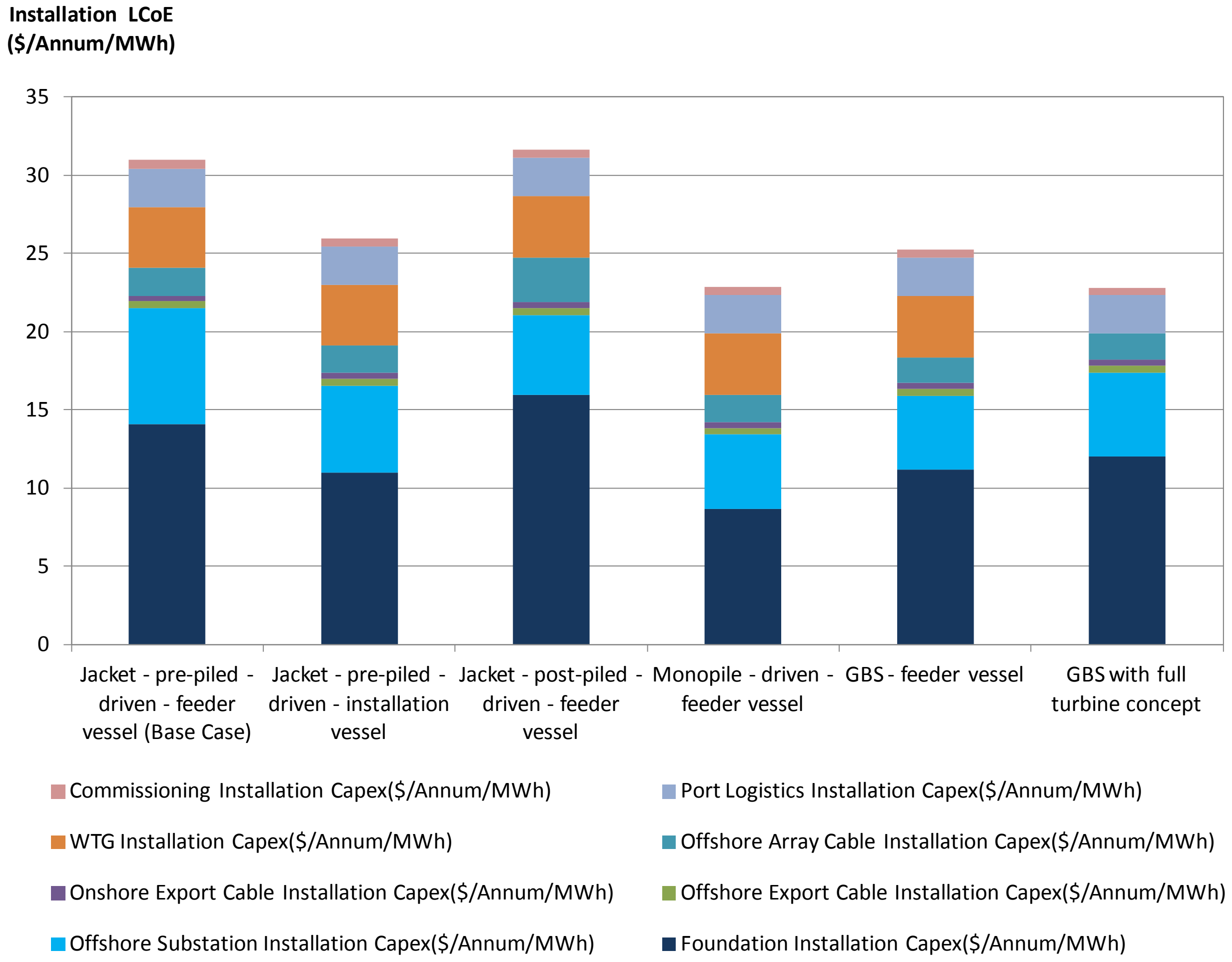


Figure 10-21: Levelized Cost of Energy for Installation and O&M with Varying Installation Methodology

Of note in Figure 10-21 is that the pre-piling of jackets results in cost savings during installation, despite the requirement for two installation vessels, this option is less expensive than for the equivalent post-piling 'driven' installation methodology due to the shorter time frame required. Also of note is that the use of the installation vessel to transport jacket foundations to the project site results in a cost saving compared to the use of feeder vessels. This shows that for the case presented above, where the wind farm is only 75 Nm from the marshaling port, the time and cost expense of the feeder barges and the subsequent offshore transfer lifts outweigh the lost time associated with the installation vessel transiting foundations between the marshaling port and the project site.

10.2.6 Sensitivity to Variation of O&M Strategy

GL GH has investigated the impact of varying O&M strategy on total O&M cost, where total O&M cost is defined here as the sum of the direct costs and lost production costs, as discussed in Section 7.2.1. GL GH has varied the access methodology and optimized repair crew resourcing accordingly, while maintaining all other base case assumptions.

Figure 10-22 presents the variation in O&M direct costs and project availability for changes in access strategy. For this particular project scenario, a helicopter in support of workboats appears to be the most favorable access strategy in terms of overall project economics. Interestingly, the OpEx associated with the helicopter access strategy is less than that of the port-based work boats, despite the additional costs associated with a helicopter. This is due to the reduced optimal number of repair crews required when a helicopter is utilized due to the improved accessibility and therefore greater resource efficiency.

The advanced access system and night-time working assumptions associated with the floatel strategy have resulted in this approach providing the highest availability. However, the reduction in lost production is insufficient to mitigate the substantial costs associated with owning and operating the floatel and daughter crafts. Whilst somewhat less expensive than the floatel, the two alternative fixed offshore base options appear to provide the least economically attractive solutions overall. This can be attributed to the limited accessibility associated with the use of work boats in conjunction with these offshore bases.

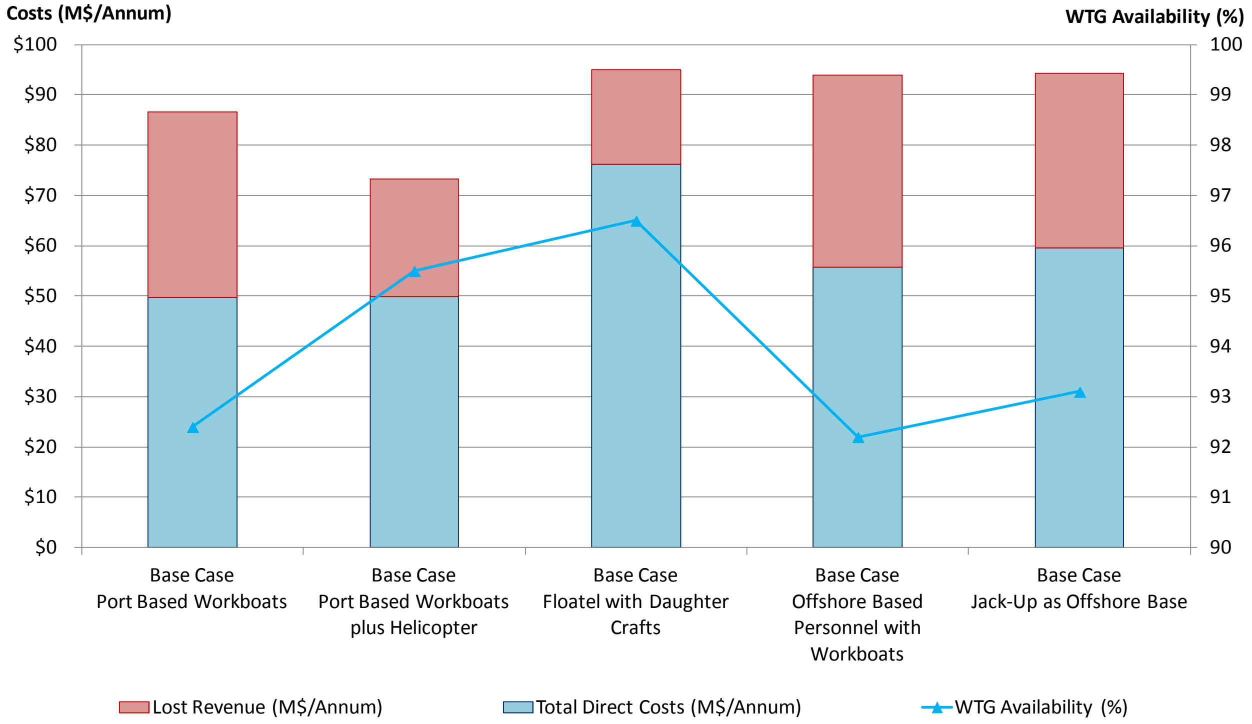


Figure 10-22: O&M Costs and WTG Availability with Varying O&M Access Strategy

11 CONCLUSIONS

GL GH has developed an Installation and O&M LCoE Analysis Tool to investigate the influence of the installation capital costs and operations and maintenance costs on the overall cost of energy within U.S. waters. As part of this investigation, GL GH has reviewed current 'state-of-the-art', as well as future, practices for offshore wind farm installation and O&M. This, combined with a review of meteorological and metocean conditions around the U.S. coast and the Great Lakes, was taken forward as part of an intensive modeling exercise to develop costs for these aspects of offshore wind projects. These costs have been combined with other assumed capital and operational costs within the Installation and O&M LCoE Analysis Tool to provide an overarching cost of energy for generic projects within U.S. waters.

The results provided within this Report are intended as a demonstration of the Installation and O&M LCoE Analysis Tool and to provide high level insight into some of the many factors which affect, and are affected by, installation and O&M at offshore wind farms. The detail provided within the companion Installation and O&M LCoE Analysis Tool empowers stakeholders to study installation and O&M activities in much greater depth and for a much broader range of project characteristics as required.

From the above investigation, and the results presented in this Report, the following general conclusions are drawn;

1. As expected, installation and O&M cost increase with the severity of a metocean climate. It is not uncommon for these costs to double their contribution to a project's overall costs of energy. This is true of changes in severity as the project is located further from the U.S. coast, but is also true as the project is located in different geographical regions around U.S. waters, with the Pacific Coastal region displaying extremely high installation and O&M costs due to the onerous climate.

2. Based on the analysis performed as part of this study, it is considered that novel installation methodologies woth reduced weather window requirements will need to be considered for the Pacific regions if economic offshore wind projects are to be realized in these locations. While the impact of the onerous metocean climate is less for O&M costs, due to the ability to access the wind turbines using helicopters, novel access methodologies would have to be developed for far-shore projects (out of shore-based range) or where larger wind turbine components require changing (which cannot be transported by helicopter).

3. Consideration will also need to be given to the installation and O&M activites within the U.S. Great Lakes region, where winter icing prevents installation during winter months and novel, untested, O&M access methodologies will have to be considered. Of particular note during winter months, when wind resource is at its peak, is the potential requirement for the change-out of larger wind turbine components that would require the attention of a jack-up vessel that would be unable to access the wind farm site.

4. Based on the analysis performed as part of this study, it is concluded that costs savings associated with installation and O&M can be achieved through the use of fewer, larger wind turbines. While there are time penalties associated with the installation of larger components offshore, these are not normally directly proportional to the capacity of the wind turbine, therefore it is possible to achieve time and, consequently, cost savings by adopting larger wind turbines. However, it should be noted that when considering this conclusion in the context of O&M costs, GL GH has not taken into consideration any changes in the reliability of wind turbine components or the durations required for their repair/replacement.

5. GL GH has assessed a number of foundation concepts and associated installation methodologies as part of the work presented here. While the choice of foundation concept is not always driven by cost, but by other technical

considerations such as a wind farm's ground conditions (seabed soils), wave climate, wind turbine size, etc., the methodology used to install these concepts can impact on costs.

6. While gravity base structures appear to provide savings in terms of installation duration and costs for some project locations and scenarios, the costs associated with the pre-installation storage of these foundations as well as the significant lead times associated with its fabrication need to be taken into consideration.

7. It should be noted that the above conclusions are a result of comparison against a single baseline case assessed using the Installation and O&M LCoE Analysis Tool. Changes in project characteristics or input costs may dramatically change the results provided by the tool and hence the results documented in this Report should be viewed as applicable only to the limited scenarios reviewed here.

8. The results presented as part of this Report are a subset of those available within the Installation and O&M LCoE Analysis Tool. The Installation and O&M LCoE Analysis Tool is intended to provide users with the ability to assess a much wider set of strategic scenarios as well as costs as individual requirements dictate.

12 REFERENCES

Reference		Document Classification
[1]	U.S. Department of Energy, "20% Wind Energy by 2030 – Increasing Wind Energy's Contribution to U.S. Electricity Supply", July 2008, sourced: http://www.nrel.gov/docs/fy08osti/41869.pdf, accessed June 2012.	Published
[2]	Navigant report Recommended Approach to Offshore Capacity Deployment Scenarios, Charlie Bloch (Navigant), Steven Kopits (Douglas-Westwood), and Eric Lantz (NREL), 25 April 2012.	Confidential
[3]	http://www.ncep.noaa.gov/, accessed June 2012.	Published
[4]	http://www.ndbc.noaa.gov/, accessed June 2012.	Published
[5]	http://www.glerl.noaa.gov/data/ice/atlas/, accessed July 2012.	Published
[6]	http://www.huismanequipment.com/afbeeldingen/album/1/_resized/happy_buccaneer_w860_h550.jpg, accessed July 2012.	Published
[7]	The International Maritime Organization, IMO: www.imo.org.	Published
[8]	http://www.imo.org/about/conventions/listofconventions/pages/international-convention-for-the-safety-of-life-at-sea-%28solas%29,-1974.aspx, accessed July 2012.	Published
[9]	COLREGs: http://www.imo.org/about/conventions/listofconventions/pages/colreg.aspx, accessed July 2012.	Published
[10]	The Maritime and Coastal Agency, MCA - http://www.mcga.gov.uk/c4mca/mcga07-home/aboutus.htm, accessed July 2012.	Published
[11]	MGN 371 - http://www.mcga.gov.uk/c4mca/mcga-mnotice.htm?textobjid=0BD60265A97A9E76, accessed July 2012.	Published
[12]	International Organization for Standarization, http://www.iso.org/iso/home.htm, accessed July 2012.	Published
[13]	http://www.dft.gov.uk/mca/mcga-mnotice.htm?textobjid=0BD60265A97A9E76, accessed July 2012.	Published

[14]	http://www.nexans.co.uk/eservice/UK-en_GB/navigate_275322/LV_and_MV_voltage_rubber_cables.html, accessed July 2012.	Published
[15]	http://www.marubeni.com/news/2012/120306e.html, accessed July 2012.	Published
[16]	http://renews.biz/strabag-shelves-offshore-wind-plans, accessed February 2013.	Published
[17]	http://www.carbontrust.com/our-clients/o/offshore-wind-accelerator#programme, accessed July 2012.	Published
[18]	http://www.carbontrust.com/media/105314/foundation_innovators_29may2012.pdf, accessed July 2012.	Published
[19]	Squire and Sanders, “Maritime Alert”, http://www.squiresanders.com/us_customs_and_border_protection_ruling_may_exempt_foreign_offshore_wind_farm_turbine-installation_vessels_from_jones_act_regulation/, accessed March 2013.	Published
[20]	Vessel List from Douglas-Westwood sent to NREL.	Confidential
[21]	http://www.windcatworkboats.com, accessed July 2012.	Published
[22]	http://www.alnmaritec.co.uk/boats/category_boats_02.html, accessed July 2012.	Published
[23]	http://www.offshorewindpower.co.uk/newvessel.htm, accessed July 2012.	Published
[24]	http://www.griffonhoverwork.com/, accessed July 2012.	Published
[25]	UK Civil Aviation Authority, “CAP 437 – Offshore Helicopter Landing Areas – Guidance on Standards”, sourced: www.caa.co.uk.	Published
[26]	http://www.uni-fly.dk/, accessed July 2012.	
[27]	http://www.bondaviationgroup.com/case-history/offshore-wind-farm-support, accessed July 2012.	
[28]	Dong Energy, Horns Rev 2 website, http://www.dongenergy.com/Hornsrev2/EN/Pages/index.aspx, accessed July 2012.	Published
[29]	http://www.seaenergy-plc.com/services/O&M/operation.html, accessed July 2012.	Published

[30]	http://floatels.biz/, accessed July 2012.	Published
[31]	Carbon Trust, “Offshore Wind Accelerator Access Competition – Shortlisted Designs”, sourced http://www.carbontrust.com/media/105302/owa-access-bg-29may2012.pdf, accessed July 2012.	Published
[32]	http://www.extremeocean.ca, accessed July 2012.	Published
[33]	http://www.fjellstrand.no/, accessed July 2012.	Published
[34]	http://www.nauti-craft.com/, accessed July 2012.	Published
[35]	http://www.northsealogistics.co.uk/, accessed July 2012.	Published
[36]	http://www.strath.ac.uk/sen/media/enterprisematters/issue24/solidseatransfer/, accessed July 2012.	Published
[37]	http://www.um.no/, accessed July 2012.	Published
[38]	http://www.otso.org.uk/Otso/Autobrow.html, accessed July 2012.	Published
[39]	http://www.bmt.org/?/51/40/2870, accessed July 2012.	Published
[40]	http://www.momac-group.de/db/docs/MOTS-presentation-GB-V110310-Handout-version.pdf, accessed July 2012.	Published
[41]	http://www.knudehansen.com/, accessed July 2012.	Published
[42]	http://www.divexglobal.com/, accessed July 2012.	Published
[43]	http://www.ztechnologies.nl, accessed July 2012.	Published
[44]	http://www.baltec.de, accessed July 2012.	Published
[45]	http://www.offshore-solutions.nl/en/products__services/the_offshore_access_system_oas_for_heavy_seas, accessed July 2012.	Published
[46]	http://www.ampelmann.nl/index.php?id=28, accessed July 2012.	Published

[47] http://www.pts-offshore.com/en/aktuell.htm, accessed July 2012. Published

[48] http://www.reflexmarine.com/, accessed July 2012. Published

[49] http://www.osbitpower.com/maxccess.html, accessed July 2012. Published

[50] http://www.fassmer.de/index.php?id=79, accessed July 2012. Published

[51] http://www.airboats.fi, accessed July 2012. Published

[52] http://arktoscraft.com/, accessed July 2012. Published

[53] http://www.glerl.noaa.gov/data/ice/atlas/. Published

APPENDIX A LEVELIZED COST OF ENERGY TOOL

This guide is intended to provide the user with some assistance on the use of the U.S. Levelized Cost of Offshore Wind Energy Model (the “Model”). The Model analyzes the installation and operational costs and logistics required for the deployment of a generic 504 MW Offshore Wind Farm in U.S. waters, combining these costs with user-defined CapEx and OpEx estimates to estimate the Levelized Cost of Energy (LCoE).

Pre-requisites:
Microsoft Office Excel 2007 or a more recent version is required to run the Model.

Set up:
Unzip the provided compressed folder and save its unzipped contents in a single folder. The Excel spread sheet uses the accompanying files stored in the folder entitled “Database”, for this reason, this folder is required to be saved in the same location as the Excel spreadsheet before running any calculations.

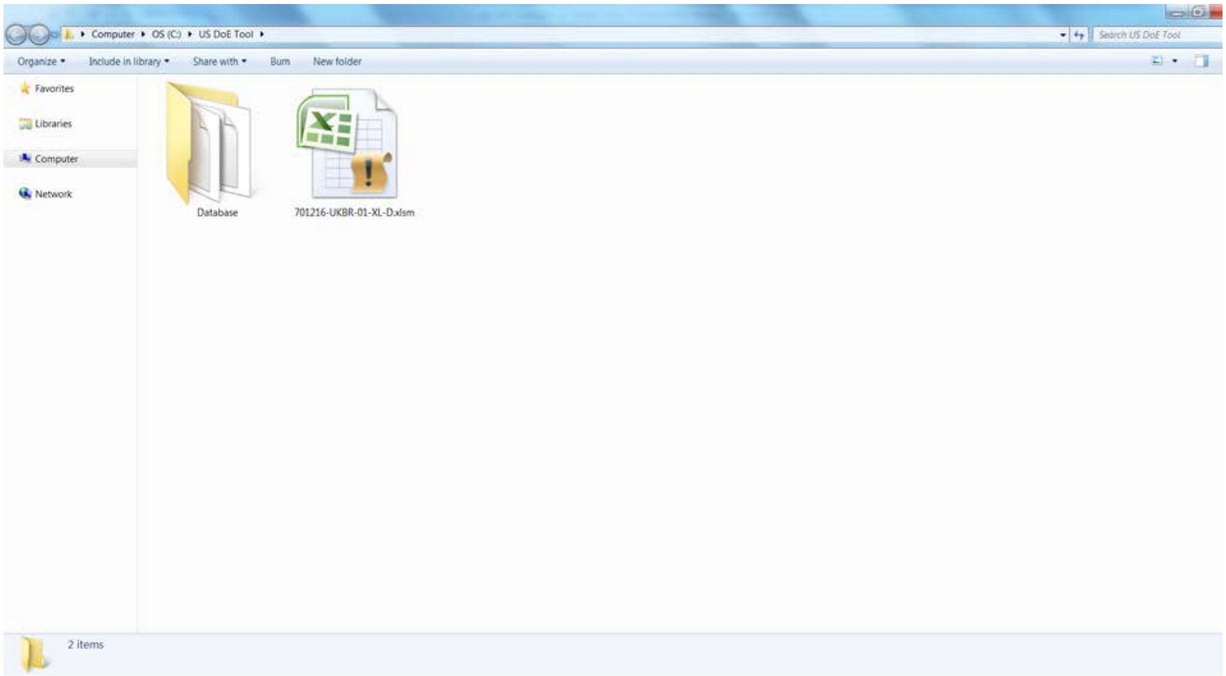


Figure A-1: File and Folder Location

Open the Excel Spread sheet. Depending on the Microsoft Office Excel version and current settings, Excel may prompt a Security Warning on the top of the sheet, in which the user MUST enable the Macros content of the workbook by clicking in Options and then on “Enable this content”, as shown in Figure A-2.

Security Warning Some active content has been disabled.

Security Alert - Macros & ActiveX

Macros & ActiveX

Macros and one or more ActiveX controls have been disabled. This active content might contain viruses or other security hazards. Do not enable this content unless you trust the source of this file.

Warning: It is not possible to determine that this content came from a trustworthy source. You should leave this content disabled unless the content provides critical functionality and you trust its source.

More information

File Path: \\GHGROUP\...liverables\121120 - Draft Deliverable Tool\701216-UKBC-01-A.xlsm

○ Help protect me from unknown content (recommended)

● Enable this content

Figure A-2: Enable Macros in Microsoft Office Excel

Once the user has enabled Macros, the Model will automatically update its database (this will take a few seconds). When finished, the worksheet: “1. Project Characteristics” will appear on the screen.

The Model is split into eight worksheets that will enable the user to vary certain project characteristics and calculate installation and Operation and Maintenance (O&M) costs and logistics as well as key performance estimates of a potential 504 MW offshore wind farm located within a certain region of the U.S.

The main Project Characteristics that the User can vary are:

1 U.S. Region

The user can select from eight different regions: Atlantic North, Atlantic Central, Atlantic South, Gulf of Mexico East, Gulf of Mexico West, Pacific North, Pacific South and the Great Lakes.

2 Wind Farm Configuration

Two wind farm configurations are available for analysis: 126 × 4 MW wind turbines and 84 × 6 MW wind turbines, both with a total capacity of 504 MW.

3 Mean Annual Significant Wave Height

The user can select from three different Mean Annual Significant Wave Heights (Hs) in meters to provide an indication of the sea-state and meteorological conditions at the site of interest.

4 Foundation Type

The User can select between four foundation types: Monopile, Jacket, Gravity Based Structures (GBS) and Semi-Sub Floating Foundations.

5 Distance to Installation Port

The user can define the distance between the offshore site of interest and the installation port by selecting from seven options within a range of 15 to 200 nautical miles (Nm).

6 Distance to O&M Port

The user can define the distance between the offshore site of interest and the O&M port by selecting from seven options within a range of 10 to 70 Nm.

Further input values such as cost assumptions, installation dates and resource logistics are required in the following worksheets while discrete options such as installation methods and O&M strategy options are given in dropdown menus.

To make best use of the Model, the user should follow the procedure outlined below:

"1. Project Characteristics"

Define the Project Characteristics that best describe the site and wind farm of interest.

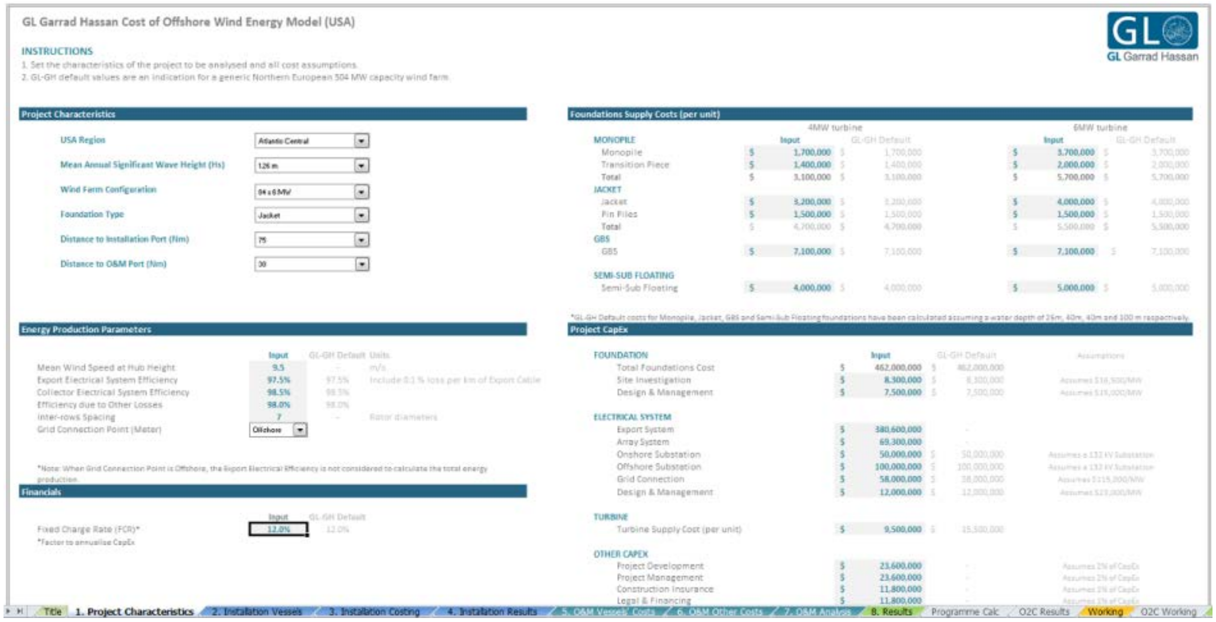
a. Project Characteristics. Allows the user to select from multiple dropdown menus, to inform the six main project characteristics described above.

b. Foundation Supply Costs. If known, indicate the supply costs per unit of the type of foundation selected. Default values are provided to give an indication of current European market costs. The Model automatically calculates the total cost of the foundations required for the selected wind farm configuration.

c. Energy Production Parameters are required in order to estimate the potential performance of the wind farm. Indicate the mean annual wind speed at hub height in meters per second (m/s) together with the respective electrical system efficiencies expected. By providing the spacing between wind turbines, the Model is able to calculate the potential losses due to wake effects. Specify the location of the Grid Connection Point, if selecting 'Offshore', the Export Electrical System Efficiency is not considered, while if 'Onshore' is selected, this export efficiency is applied to the final energy production.

d. Financials. In order to annualize the CapEx of the project, the user MUST indicate a Fixed Charge Rate.

e. Project Capital Expenditure (CapEx). Check or amend the Project CapEx required for the wind farm under consideration. These costs entail: Site Investigation, Design and Management, Export Electrical System, Array Electrical System, Onshore Substation, Offshore Substation, Grid Connection, Turbine Supply Cost, Project Development, Project Management, Construction Insurance, Legal and Financing and Contingency.



GL Garrad Hassan Cost of Offshore Wind Energy Model (USA)

INSTRUCTIONS
1. Set the characteristics of the project to be analysed and all cost assumptions.
2. GL-GH default values are an indication for a generic Northern European 504 MW capacity wind farm.

Project Characteristics

USA Region: Atlantic Central
Mean Annual Significant Wave Height (Hs): 1.26 m
Wind Farm Configuration: 84 x 6 MW
Foundation Type: Jacket
Distance to Installation Port (Nm): 75
Distance to O&M Port (Nm): 30

Energy Production Parameters

	Input	GL-GH Default	Units
Mean Wind Speed at Hub Height	9.5	-	m/s
Export Electrical System Efficiency	97.5%	97.5%	Include 0.1 % loss per km of Export Cable
Collector Electrical System Efficiency	98.5%	98.5%	
Efficiency due to Other Losses	98.0%	98.0%	
Inter-rows Spacing	7	-	Rotor diameters
Grid Connection Point (Meter)	Offshore		

*Note: When Grid Connection Point is Offshore, the Export Electrical Efficiency is not considered to calculate the total energy production.

Financials

	Input	GL-GH Default
Fixed Charge Rate (FCR)*	12.0%	12.0%

*Factor to annualise CapEx

Foundations Supply Costs (per unit)

	4MW turbine		6MW turbine	
	Input	GL-GH Default	Input	GL-GH Default
MONOPILE				
Monopile	$ 1,700,000	$ 1,700,000	$ 3,700,000	$ 3,700,000
Transition Piece	$ 1,400,000	$ 1,400,000	$ 2,000,000	$ 2,000,000
Total	$ 3,100,000	$ 3,100,000	$ 5,700,000	$ 5,700,000
JACKET				
Jacket	$ 3,200,000	$ 3,200,000	$ 4,000,000	$ 4,000,000
Pin Piles	$ 1,500,000	$ 1,500,000	$ 1,500,000	$ 1,500,000
Total	$ 4,700,000	$ 4,700,000	$ 5,500,000	$ 5,500,000
GBS				
GBS	$ 7,100,000	$ 7,100,000	$ 7,100,000	$ 7,100,000
SEMI-SUB FLOATING				
Semi-Sub Floating	$ 4,000,000	$ 4,000,000	$ 5,000,000	$ 5,000,000

*GL-GH Default costs for Monopile, Jacket, GBS and Semi-Sub Floating foundations have been calculated assuming a water depth of 25m, 40m, 40m and 100 m respectively.

Project CapEx

	Input	GL-GH Default	Assumptions
FOUNDATION			
Total Foundations Cost	$ 462,000,000	$ 462,000,000	
Site Investigation	$ 8,300,000	$ 8,300,000	Assumes $16,500/MW
Design & Management	$ 7,500,000	$ 7,500,000	Assumes $15,000/MW
ELECTRICAL SYSTEM			
Export System	$ 380,600,000	-	
Array System	$ 69,300,000	-	
Onshore Substation	$ 50,000,000	$ 50,000,000	Assumes a 132 kV Substation
Offshore Substation	$ 100,000,000	$ 100,000,000	Assumes a 132 kV Substation
Grid Connection	$ 58,000,000	$ 58,000,000	Assumes $115,000/MW
Design & Management	$ 12,000,000	$ 12,000,000	Assumes $23,000/MW
TURBINE			
Turbine Supply Cost (per unit)	$ 9,500,000	$ 15,500,000	
OTHER CAPEX			
Project Development	$ 23,600,000	-	Assumes 2% of CapEx
Project Management	$ 23,600,000	-	Assumes 2% of CapEx
Construction Insurance	$ 11,800,000	-	Assumes 1% of CapEx
Legal & Financing	$ 11,800,000	-	Assumes 1% of CapEx

Figure A-3: Project Characteristics Input Sheet

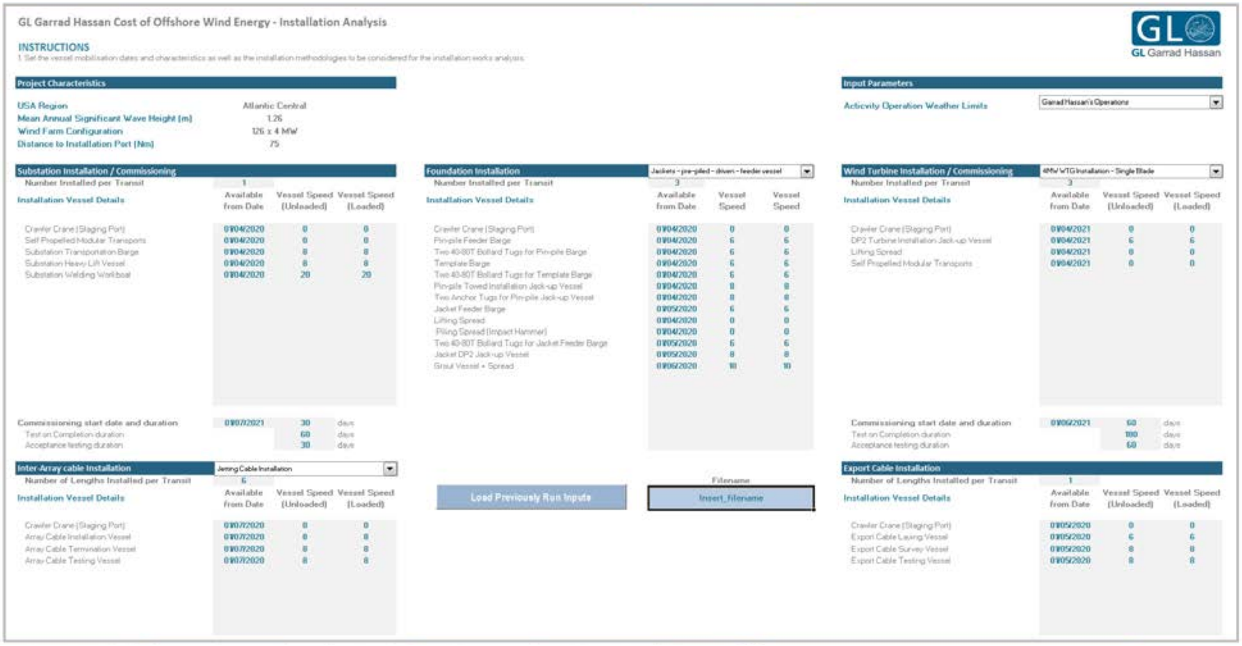
"2. Installation Vessels"

Select the installation methodology for each component of the wind farm and indicate the date from which each of the required vessels is available to start the installation works. In addition, specify the number of units that the vessel can install per transit to site.

a. Installation Methodology. The Model allows the user to select an installation methodology for each component of the wind farm. GL GH has provided a recommended list of vessels and characteristics for each installation methodology; which will appear once the user has made a selection in the *"1. Project Characteristics"* sheet. However, the user is able to overwrite required vessels, vessel speeds, and number of components installed per transit, if desired.

b. Input Parameters. The user is able to specify operational limits for the selected installation activities. GL GH has inputted a set of default limits which can be utilized by selecting "Garrad Hassan's Operations" or the user can define their own sub-operations and limitations by selecting "User Defined Operations". By Selecting "User Defined Operations" all Installation Vessel Details will be cleared and the user should fill these parameters for each of the components according to its installation requirements. In addition to this information, the user must also fill the duration and weather limitations of the selected vessels in the Additional Inputs Sheets as described in Section 3 below.

c. Load Previously Run Inputs. If the user has previously ran installation simulations and wishes to use the same inputs used, it is possible to load these inputs by writing the previous file name and clicking "Load Previously Run Inputs". By doing this, the tool will look for the saved inputs file and reload all the "Project characteristics" as well as the "Installation Vessel Details". It must be noted that cost inputs aren't saved; therefore if the user has modified these values, this will affect the final costing outputs.



GL Garrad Hassan Cost of Offshore Wind Energy - Installation Analysis

INSTRUCTIONS

1 Set the vessel mobilisation dates and characteristics as well as the installation methodologies to be considered for the installation works analysis.

Project Characteristics

USA Region	Atlantic Central
Mean Annual Significant Wave Height (m)	1.26
Wind Farm Configuration	126 x 4 MW
Distance to Installation Port (Nm)	75

Input Parameters

Acticvity Operation Weather Limits: Garrad Hassan's Operations

Substation Installation / Commissioning

Number Installed per Transit: 1

Installation Vessel Details	Available from Date	Vessel Speed (Unloaded)	Vessel Speed (Loaded)
Crawler Crane (Staging Port)	01/04/2020	0	0
Self Propelled Modular Transports	01/04/2020	0	0
Substation Transportation Barge	01/04/2020	8	8
Substation Heavy Lift Vessel	01/04/2020	8	8
Substation Welding Workboat	01/04/2020	20	20

Commissioning start date and duration	01/07/2021	30	days
Test on Completion duration		60	days
Acceptance testing duration		30	days

Foundation Installation: Jackets - pre-piled - driven - feeder vessel

Number Installed per Transit: 3

Installation Vessel Details	Available from Date	Vessel Speed	Vessel Speed
Crawler Crane (Staging Port)	01/04/2020	0	0
Pin-pile Feeder Barge	01/04/2020	6	6
Two 40-80T Bollard Tugs for Pin-pile Barge	01/04/2020	6	6
Template Barge	01/04/2020	6	6
Two 40-80T Bollard Tugs for Template Barge	01/04/2020	6	6
Pin-pile Towed Installation Jack-up Vessel	01/04/2020	0	0
Two Anchor Tugs for Pin-pile Jack-up Vessel	01/04/2020	8	8
Jacket Feeder Barge	01/05/2020	6	6
Lifting Spread	01/04/2020	0	0
Piling Spread (Impact Hammer)	01/04/2020	0	0
Two 40-80T Bollard Tugs for Jacket Feeder Barge	01/05/2020	6	6
Jacket DP2 Jack-up Vessel	01/05/2020	8	8
Grout Vessel + Spread	01/06/2020	10	10

Wind Turbine Installation / Commissioning: 4MW WTG Installation - Single Blade

Number Installed per Transit: 3

Installation Vessel Details	Available from Date	Vessel Speed (Unloaded)	Vessel Speed (Loaded)
Crawler Crane (Staging Port)	01/04/2021	0	0
DP2 Turbine Installation Jack-up Vessel	01/04/2021	6	6
Lifting Spread	01/04/2021	0	0
Self Propelled Modular Transports	01/04/2021	0	0

Commissioning start date and duration	01/06/2021	60	days
Test on Completion duration		180	days
Acceptance testing duration		60	days

Inter-Array cable Installation: Jetting Cable Installation

Number of Lengths Installed per Transit: 6

Installation Vessel Details	Available from Date	Vessel Speed (Unloaded)	Vessel Speed (Loaded)
Crawler Crane (Staging Port)	01/07/2020	0	0
Array Cable Installation Vessel	01/07/2020	8	8
Array Cable Termination Vessel	01/07/2020	8	8
Array Cable Testing Vessel	01/07/2020	8	8

Export Cable Installation

Number of Lengths Installed per Transit: 1

Installation Vessel Details	Available from Date	Vessel Speed (Unloaded)	Vessel Speed (Loaded)
Crawler Crane (Staging Port)	01/05/2020	0	0
Export Cable Laying Vessel	01/05/2020	6	6
Export Cable Survey Vessel	01/05/2020	8	8
Export Cable Testing Vessel	01/05/2020	8	8

Figure A-4: Installation Vessels Input Sheet

"3. Installation Costing"

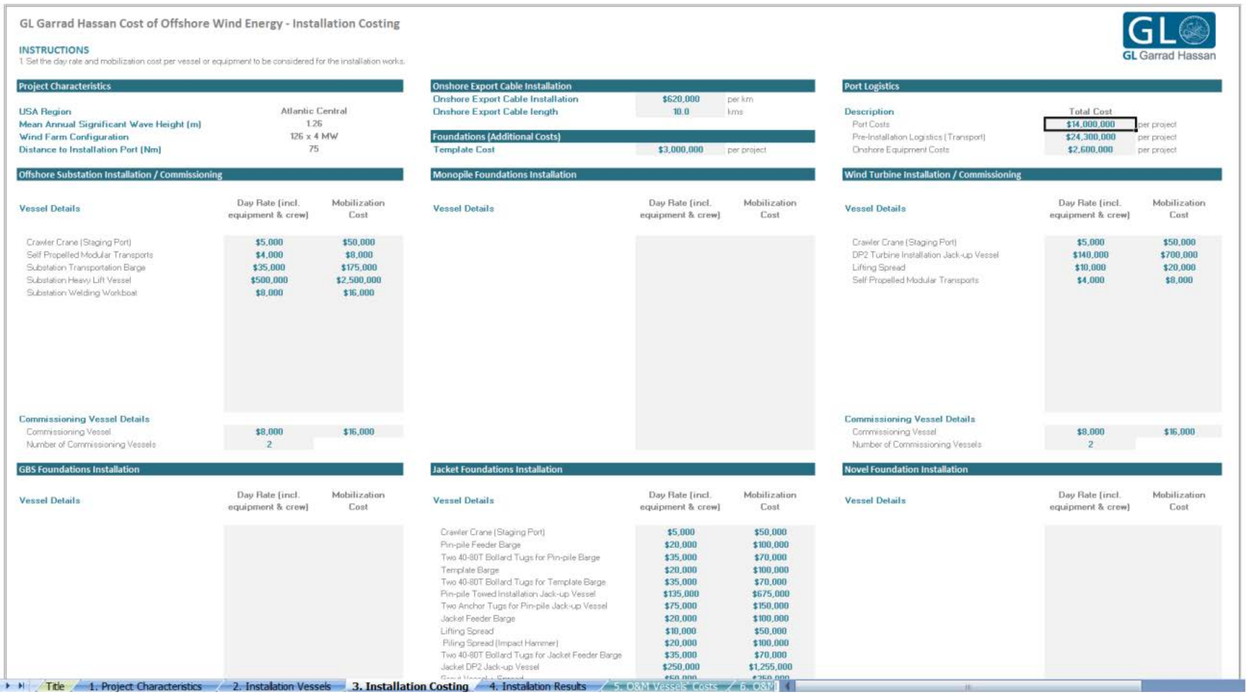
Set the mobilization costs and day rates per vessel or equipment required for the installation of the wind farm of interest.

a. Vessel Details. If the user has selected "Garrad Hassan's Operations", a list of recommended vessels for each installation activity will be provided, in addition to typical mobilization costs and day rates which can be altered by the user. Alternatively, if the user has selected "User Defined Operations" the sheet is left blank for the user to infill their own vessels and related values for each installation activity.

b. Mobilization Costs cover the preparation of a vessel before transit to the site. This could involve the modification of the vessel and/or the mobilization of the crew required to operate it. These costs are incurred each time the vessel is deployed to site.

c. Port Logistics Costs cover port utilization fees, transport and onshore logistics.

d. Additional Input Sheets. Once the user has specified their preferred installation methodology and vessels, additional user input sheets for each installation activity are updated. These will contain either GL GH's default limits or if the user has selected "User Defined Operations", these will be blank for the user to complete. In order to fill the activity sheets, the user MUST expand the rows of each sub-operation by clicking on the plus sign to the left of each sub-operation heading. This allows the user to define sub-operations and limitations. The user MUST also select which vessels are necessary for each operation. The dropdown menu should be set to "Mobilized" for the first operation for which a vessel is needed and "Required" for every further operation until no longer necessary. It is important to note that when selecting "User Defined Operations", all sub-operations will be dependent on the previous sub-operation within each Activity and parallel sub-operations won't be enabled, however, different activities could still run in parallel.



GL Garrad Hassan Cost of Offshore Wind Energy - Installation Costing

INSTRUCTIONS

1 Set the day rate and mobilization cost per vessel or equipment to be considered for the installation works.

Project Characteristics

USA Region	Atlantic Central
Mean Annual Significant Wave Height (m)	1.26
Wind Farm Configuration	126 x 4 MW
Distance to Installation Port (Nm)	75

Onshore Export Cable Installation

Onshore Export Cable Installation	$620,000	per km
Onshore Export Cable length	10.0	kms

Foundations (Additional Costs)

Template Cost	$3,000,000	per project

Port Logistics

Description	Total Cost	
Port Costs	$14,000,000	per project
Pre-Installation Logistics (Transport)	$24,300,000	per project
Onshore Equipment Costs	$2,600,000	per project

Offshore Substation Installation / Commissioning

Vessel Details	Day Rate (incl. equipment & crew)	Mobilization Cost
Crawler Crane (Staging Port)	$5,000	$50,000
Self Propelled Modular Transports	$4,000	$8,000
Substation Transportation Barge	$35,000	$175,000
Substation Heavy Lift Vessel	$500,000	$2,500,000
Substation Welding Workboat	$8,000	$16,000
Commissioning Vessel Details		
Commissioning Vessel	$8,000	$16,000
Number of Commissioning Vessels	2	

Monopile Foundations Installation

Vessel Details	Day Rate (incl. equipment & crew)	Mobilization Cost

Wind Turbine Installation / Commissioning

Vessel Details	Day Rate (incl. equipment & crew)	Mobilization Cost
Crawler Crane (Staging Port)	$5,000	$50,000
DP2 Turbine Installation Jack-up Vessel	$140,000	$700,000
Lifting Spread	$10,000	$20,000
Self Propelled Modular Transports	$4,000	$8,000
Commissioning Vessel Details		
Commissioning Vessel	$8,000	$16,000
Number of Commissioning Vessels	2	

GBS Foundations Installation

Vessel Details	Day Rate (incl. equipment & crew)	Mobilization Cost

Jacket Foundations Installation

Vessel Details	Day Rate (incl. equipment & crew)	Mobilization Cost
Crawler Crane (Staging Port)	$5,000	$50,000
Pin-pile Feeder Barge	$20,000	$100,000
Two 40-80T Bollard Tugs for Pin-pile Barge	$35,000	$70,000
Template Barge	$20,000	$100,000
Two 40-80T Bollard Tugs for Template Barge	$35,000	$70,000
Pin-pile Towed Installation Jack-up Vessel	$135,000	$675,000
Two Anchor Tugs for Pin-pile Jack-up Vessel	$75,000	$150,000
Jacket Feeder Barge	$20,000	$100,000
Lifting Spread	$10,000	$50,000
Piling Spread (Impact Hammer)	$20,000	$100,000
Two 40-80T Bollard Tugs for Jacket Feeder Barge	$35,000	$70,000
Jacket DP2 Jack-up Vessel	$250,000	$1,255,000

Novel Foundation Installation

Vessel Details	Day Rate (incl. equipment & crew)	Mobilization Cost

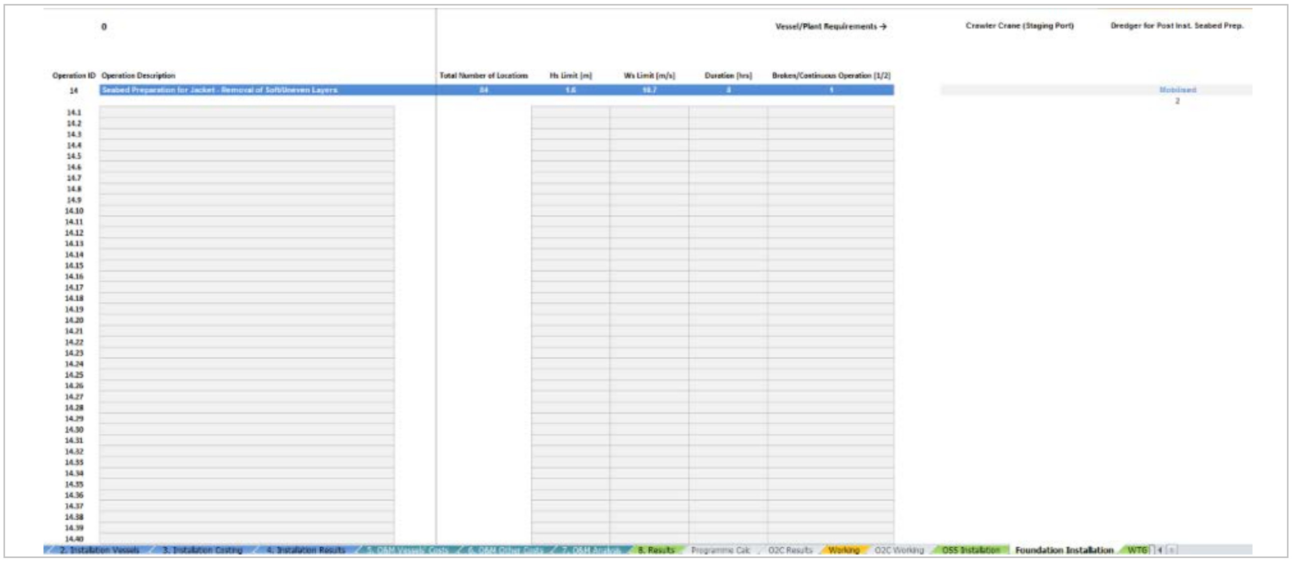
Figure A-5: Installation Costing Input Sheet

0

Vessel/Plant Requirements →

Operation ID	Operation Description	Total Number of Locations	Hs Limit [m]	Ws Limit [m/s]	Duration [hrs]	Broken/Continuous Operation [1/2]	Crawler Crane (Staging Port)
14	Seabed Preparation for Jacket - Removal of Soft/Uneven Layers	84	1.6	10.7	8	1	
15	Load Out Fall-pipe Vessel	84	999.0	17.1	25	1	Mobilised
16	Fall-pipe Vessel Transits to Site	84	2.7	17.1	9	1	Required
17	Deposit Rock Layer with Fall-pipe Vessel	84	2.2	13.8	2	1	Required
18	Fall-pipe Vessel Transits to Port	84	2.2	13.8	9	1	Required
19	Positioning of Feeder Barge	84	1.6	10.7	1	1	Required
20	Load Out of Pin-piles and Jackets to Feeder Barge	84	1.1	7.9	9	1	Required
21	Preparation of Feeder Barge for Transit	84	2.2	13.8	1	1	Required
22	Feeder Barge Transits to Site	84	2.2	13.8	13	1	Required
23	Installation of Jacket and Pin-piles from Feeder Barge	84	1.1	7.9	116	1	Required
24	Feeder Barge Transits to Port	84	2.2	13.8	13	1	Required
25	Load Out Grout Vessel	84	999.0	13.8	8	1	
26	Grout Vessel Transits to Site	84	2.2	13.8	8	1	
27	Grout Jacket	84	2.2	13.8	9	1	
28	Grout Vessel Transits to Port	84	2.2	13.8	8	1	
29	Null	84	999.0	999.0	0	1	
30	Null	84	999.0	999.0	0	1	
31	Null	84	999.0	999.0	0	1	
32	Null	84	999.0	999.0	0	1	
33	Null	84	999.0	999.0	0	1	
34	Null	84	999.0	999.0	0	1	

Figure A-6: Additional User Input Sheets



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Vessel/Plant Requirements →

Operation ID	Operation Description	Total Number of Locations	Hs Limit (m)	Ws Limit (m/s)	Duration (hrs)	Broken/Continuous Operation (1/2)	Crawler Crane (Staging Port)	Dredger for Post Inst. Seabed Prep.
14	Seabed Preparation for Jacket - Removal of Soft/Uneven Layers	84	1.6	10.7	8	1		Mobilised 2
14.1								
14.2								
14.3								
14.4								
14.5								
14.6								
14.7								
14.8								
14.9								
14.10								
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14.40								

Figure A-7: Expanded Additional Input Sheets

"4. Installation Results"

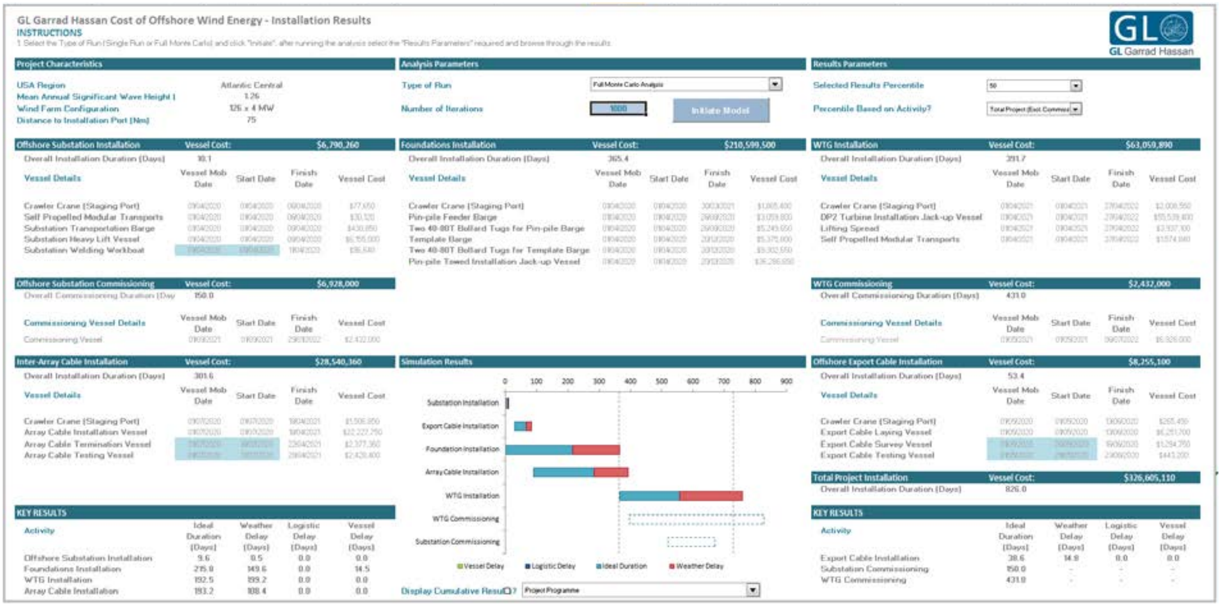
Select the type of run from the dropdown menu and click "Initiate Model" in order to obtain results.

a. <u>"Single Run (P50 Inputs)"</u> will output results in under a minute; the tool will complete a single iteration utilizing P50 input parameters.

b. <u>"Full Monte Carlo Analysis"</u> performs 1000 iterations which can take up to a few hours building up a probability distribution of output results. The user can also input the number of iterations if required. For this simulation type, it is strongly recommended to save the tool and the "Database" folder in a local drive (C:) and to disable the "Sleep", "Lock User" and "Hibernate" functions of the computer to be used for the analysis. This will allow the tool to run without interruptions.

c. <u>Results Parameters.</u> Once a full Monte Carlo analysis has been run, the user can quickly analyze the results by selecting a percentile and the activity that percentile is based on from the dropdown menus.

When running a simulation the model will request a name to save the results files. These files are saved in the database folder, if a previous run has been made with the given filename the user can load those results without having to wait for the simulation to be rerun.



GL Garrad Hassan Cost of Offshore Wind Energy - Installation Results

INSTRUCTIONS

1. Select the Type of Run (Single Run or Full Monte Carlo) and click "Initiate", after running the analysis select the "Results Parameters" required and browse through the results.

Project Characteristics

USA Region	Atlantic Central
Mean Annual Significant Wave Height (	1.26
Wind Farm Configuration	125 x 4 MW
Distance to Installation Port (Nm)	75

Analysis Parameters

Type of Run: Full Monte Carlo Analysis

Number of Iterations: 1000

Results Parameters

Selected Results Percentile: 50

Percentile Based on Activity?: Total Project (Excl Commiss

Offshore Substation Installation Vessel Cost: $6,790,260

Overall Installation Duration (Days) 10.1

Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Crawler Crane (Staging Port)	[illegible]	[illegible]	[illegible]	[illegible]
Self Propelled Modular Transports	[illegible]	[illegible]	[illegible]	[illegible]
Substation Transportation Barge	[illegible]	[illegible]	[illegible]	[illegible]
Substation Heavy Lift Vessel	[illegible]	[illegible]	[illegible]	[illegible]
Substation Welding Workboat	[illegible]	[illegible]	[illegible]	[illegible]

Foundations Installation Vessel Cost: $210,599,500

Overall Installation Duration (Days) 365.4

Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Crawler Crane (Staging Port)	[illegible]	[illegible]	[illegible]	[illegible]
Pin-pile Feeder Barge	[illegible]	[illegible]	[illegible]	[illegible]
Two 40-80T Bollard Tugs for Pin-pile Barge	[illegible]	[illegible]	[illegible]	[illegible]
Template Barge	[illegible]	[illegible]	[illegible]	[illegible]
Two 40-80T Bollard Tugs for Template Barge	[illegible]	[illegible]	[illegible]	[illegible]
Pin-pile Towed Installation Jack-up Vessel	[illegible]	[illegible]	[illegible]	[illegible]

WTG Installation Vessel Cost: $63,059,890

Overall Installation Duration (Days) 391.7

Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Crawler Crane (Staging Port)	[illegible]	[illegible]	[illegible]	[illegible]
DP2 Turbine Installation Jack-up Vessel	[illegible]	[illegible]	[illegible]	[illegible]
Lifting Spread	[illegible]	[illegible]	[illegible]	[illegible]
Self Propelled Modular Transports	[illegible]	[illegible]	[illegible]	[illegible]

Offshore Substation Commissioning Vessel Cost: $6,928,000

Overall Commissioning Duration (Day 150.0

Commissioning Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Commissioning Vessel	[illegible]	[illegible]	[illegible]	[illegible]

WTG Commissioning Vessel Cost: $2,432,000

Overall Commissioning Duration (Days) 431.0

Commissioning Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Commissioning Vessel	[illegible]	[illegible]	[illegible]	[illegible]

Inter-Array Cable Installation Vessel Cost: $28,540,360

Overall Installation Duration (Days) 301.6

Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Crawler Crane (Staging Port)	[illegible]	[illegible]	[illegible]	[illegible]
Array Cable Installation Vessel	[illegible]	[illegible]	[illegible]	[illegible]
Array Cable Termination Vessel	[illegible]	[illegible]	[illegible]	[illegible]
Array Cable Testing Vessel	[illegible]	[illegible]	[illegible]	[illegible]

Offshore Export Cable Installation Vessel Cost: $8,255,100

Overall Installation Duration (Days) 53.4

Vessel Details	Vessel Mob Date	Start Date	Finish Date	Vessel Cost
Crawler Crane (Staging Port)	[illegible]	[illegible]	[illegible]	[illegible]
Export Cable Laying Vessel	[illegible]	[illegible]	[illegible]	[illegible]
Export Cable Survey Vessel	[illegible]	[illegible]	[illegible]	[illegible]
Export Cable Testing Vessel	[illegible]	[illegible]	[illegible]	[illegible]

Total Project Installation Vessel Cost: $326,605,110

Overall Installation Duration (Days) 826.0

Simulation Results

Display Cumulative Results? Project Programme

KEY RESULTS

Activity	Ideal Duration (Days)	Weather Delay (Days)	Logistic Delay (Days)	Vessel Delay (Days)
Offshore Substation Installation	9.6	0.5	0.0	0.0
Foundations Installation	215.0	149.6	0.0	14.5
WTG Installation	192.5	199.2	0.0	0.0
Array Cable Installation	193.2	108.4	0.0	0.0

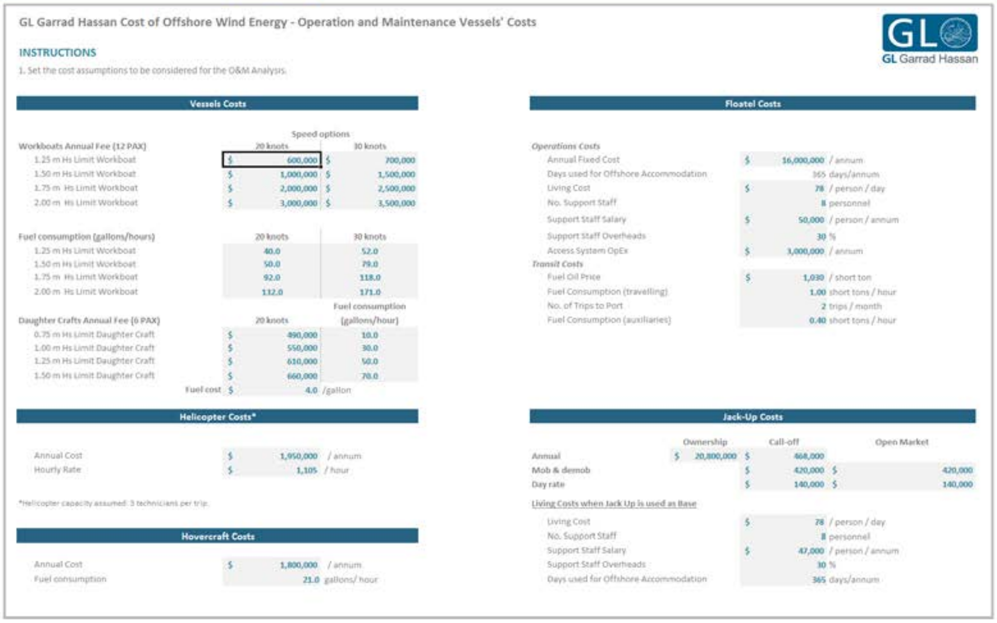
KEY RESULTS

Activity	Ideal Duration (Days)	Weather Delay (Days)	Logistic Delay (Days)	Vessel Delay (Days)
Export Cable Installation	38.6	14.8	0.0	0.0
Substation Commissioning	150.0	-	-	-
WTG Commissioning	431.0	-	-	-

Figure A-8: Installation Results Sheet

"5. O&M Vessels' Costs"

Check or amend the cost of: Work Boats, Mothership-based Daughter Crafts, Helicopters, Hovercraft, O&M Jack-up Vessel and a Floatel. All these costs will be used for the O&M Analysis and Strategy Optimization performed in worksheet: "7.O&M Analysis".



GL Garrad Hassan Cost of Offshore Wind Energy - Operation and Maintenance Vessels' Costs

INSTRUCTIONS

1. Set the cost assumptions to be considered for the O&M Analysis.

Vessels Costs

Workboats Annual Fee (12 PAX)	Speed options 20 knots	30 knots
1.25 m Hs Limit Workboat	$ 600,000	$ 700,000
1.50 m Hs Limit Workboat	$ 1,000,000	$ 1,500,000
1.75 m Hs Limit Workboat	$ 2,000,000	$ 2,500,000
2.00 m Hs Limit Workboat	$ 3,000,000	$ 3,500,000

Fuel consumption (gallons/hours)	20 knots	30 knots
1.25 m Hs Limit Workboat	40.0	52.0
1.50 m Hs Limit Workboat	50.0	79.0
1.75 m Hs Limit Workboat	92.0	118.0
2.00 m Hs Limit Workboat	112.0	171.0

Daughter Crafts Annual Fee (6 PAX)	20 knots	Fuel consumption (gallons/hour)
0.75 m Hs Limit Daughter Craft	$ 490,000	10.0
1.00 m Hs Limit Daughter Craft	$ 550,000	30.0
1.25 m Hs Limit Daughter Craft	$ 610,000	50.0
1.50 m Hs Limit Daughter Craft	$ 660,000	70.0
Fuel cost	$ 4.0	/gallon

Helicopter Costs*

Annual Cost	$ 1,950,000	/ annum
Hourly Rate	$ 1,105	/ hour

*Helicopter capacity assumed: 3 technicians per trip.

Hovercraft Costs

Annual Cost	$ 1,800,000	/ annum
Fuel consumption	21.0	gallons/ hour

Floatel Costs

Operations Costs		
Annual Fixed Cost	$ 16,000,000	/ annum
Days used for Offshore Accommodation	365	days/annum
Living Cost	$ 78	/ person / day
No. Support Staff	8	personnel
Support Staff Salary	$ 50,000	/ person / annum
Support Staff Overheads	30	%
Access System OpEx	$ 3,000,000	/ annum
Transit Costs		
Fuel Oil Price	$ 1,030	/ short ton
Fuel Consumption (travelling)	1.00	short tons / hour
No. of Trips to Port	2	trips / month
Fuel Consumption (auxiliaries)	0.40	short tons / hour

Jack-Up Costs

	Ownership	Call-off	Open Market
Annual	$ 20,800,000	$ 468,000	
Mob & demob		$ 420,000	$ 420,000
Day rate		$ 140,000	$ 140,000

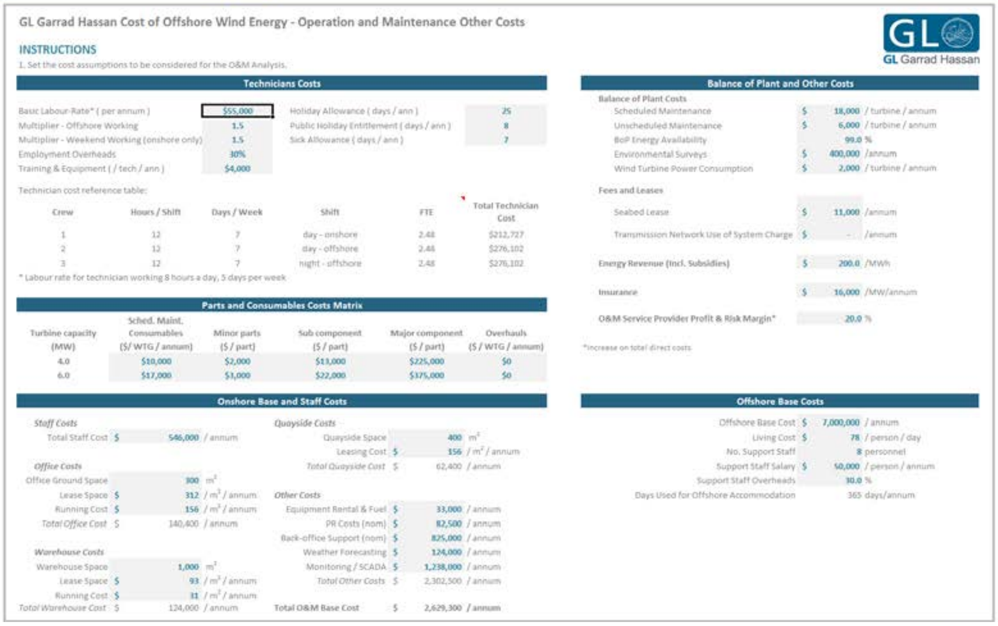
Living Costs when Jack Up is used as Base

Living Cost	$ 78	/ person / day
No. Support Staff	8	personnel
Support Staff Salary	$ 47,000	/ person / annum
Support Staff Overheads	30	%
Days used for Offshore Accommodation	365	days/annum

Figure A-9: O&M Vessel Costs Input Sheet

“6. O&M Other Costs”

Check or amend the cost of Technicians, Parts and Consumables, Onshore Base and Staff Costs, Balance of Plant and Offshore Base Costs. All these costs will be used for the O&M Analysis and Strategy Optimization performed in worksheet: “7.O&M Analysis”.



GL Garrad Hassan Cost of Offshore Wind Energy - Operation and Maintenance Other Costs

INSTRUCTIONS

1. Set the cost assumptions to be considered for the O&M Analysis.

Technicians Costs

Basic Labour Rate* (per annum)	$55,000	Holiday Allowance (days / ann)	25
Multiplier - Offshore Working	1.5	Public Holiday Entitlement (days / ann)	8
Multiplier - Weekend Working (onshore only)	1.5	Sick Allowance (days / ann)	7
Employment Overheads	30%		
Training & Equipment (/ tech / ann)	$4,000		

Technician cost reference table:

Crew	Hours / Shift	Days / Week	Shift	FTE	Total Technician Cost
1	12	7	day - onshore	2.48	$212,727
2	12	7	day - offshore	2.48	$276,102
3	12	7	night - offshore	2.48	$276,102

* Labour rate for technician working 8 hours a day, 5 days per week

Parts and Consumables Costs Matrix

Turbine capacity (MW)	Sched. Maint. Consumables ($/ WTG / annum)	Minor parts ($ / part)	Sub component ($ / part)	Major component ($ / part)	Overhauls ($ / WTG / annum)
4.0	$10,000	$2,000	$13,000	$225,000	$0
6.0	$17,000	$3,000	$22,000	$375,000	$0

Onshore Base and Staff Costs

Staff Costs

Total Staff Cost	$	546,000	/ annum

Office Costs

Office Ground Space		300	m^2
Lease Space	$	312	/ m^2 / annum
Running Cost	$	156	/ m^2 / annum
Total Office Cost	$	140,400	/ annum

Warehouse Costs

Warehouse Space		1,000	m^2
Lease Space	$	93	/ m^2 / annum
Running Cost	$	31	/ m^2 / annum
Total Warehouse Cost	$	124,000	/ annum

Quayside Costs

Quayside Space		400	m^2
Leasing Cost	$	156	/ m^2 / annum
Total Quayside Cost	$	62,400	/ annum

Other Costs

Equipment Rental & Fuel	$	33,000	/ annum
PR Costs (nom)	$	82,500	/ annum
Back-office Support (nom)	$	825,000	/ annum
Weather Forecasting	$	124,000	/ annum
Monitoring / SCADA	$	1,238,000	/ annum
Total Other Costs	$	2,302,500	/ annum
Total O&M Base Cost	$	2,629,300	**/ annum**

Balance of Plant and Other Costs

Balance of Plant Costs			
Scheduled Maintenance	$	18,000	/ turbine / annum
Unscheduled Maintenance	$	6,000	/ turbine / annum
BoP Energy Availability		99.0	%
Environmental Surveys	$	400,000	/annum
Wind Turbine Power Consumption	$	2,000	/ turbine / annum
Fees and Leases			
Seabed Lease	$	11,000	/annum
Transmission Network Use of System Charge	$	-	/annum
Energy Revenue (incl. Subsidies)	$	200.0	/MWh
Insurance	$	16,000	/MW/annum
O&M Service Provider Profit & Risk Margin*		20.0	%

*increase on total direct costs

Offshore Base Costs

Offshore Base Cost	$	7,000,000	/ annum
Living Cost	$	78	/ person / day
No. Support Staff		8	personnel
Support Staff Salary	$	50,000	/ person / annum
Support Staff Overheads		30.0	%
Days Used for Offshore Accommodation		365	days/annum

Figure A-10: O&M Other Costs Input Sheet

“7. O&M Analysis”

Select the expected Wind Turbine Reliability and the O&M Jack-Up Contracting Options and optimize the O&M Strategy. The options available in this analysis are:

1) WTG Reliability. The user can select from three different WTG Reliabilities:

- Degraded Reliability. Applies a 20% increase on the central rate of failures per turbine per year.
- Central Reliability. Uses typical failure rates from European Offshore wind industry experience.
- Improved Reliability. Applies a 20% reduction on the central rate of failures per turbine per year.

2) O&M Jack-Up Contracting Strategy. Costs associated with Jack-up barges are heavily dependent on the contracting strategy undertaken, therefore the user can select from the following options:

- *Ownership* of a Jack-Up barge applies a single high annual cost associated with this O&M scenario.
- *Open Market* implies a mobilization and demobilization cost is incurred every time the vessel is called out; it also includes a day rate which is payable for the duration of the necessary works.
- *Call-off* applies an annual retainer fee typically paid to ensure shorter lead times than on the Open Market approach. Mobilization and demobilization costs are still applied, as well as a fixed day rate payable for the duration of the necessary works.

3) **Jack-Up lead time.** The user has the option to specify the Jack-Up lead time, which is the time from ordering a Jack-Up vessel until it is ready to work at the O&M port. Note that when the *Ownership* contracting strategy is selected, the Model disables the lead time input box and fixes a lead time of 3 days, this is to consider that when owning the vessel, it is always ready for work in short time.

After setting up the Reliability and Contracting Strategy Options, the Model is now ready to evaluate the optimal O&M Strategy. In order to obtain the optimal strategy, the Model searches for the combination of O&M Strategy Options which provide the lowest Total O&M Cost. This Total O&M Cost takes account of both the level of investment in the O&M of the project (Total Direct O&M Costs) as well as the value of the energy production (Lost Production Costs).

Total O&M Cost = Direct O&M Costs + Lost Production Costs

Minimization of the Total O&M Costs therefore represents the maximization of profits from the wind farm. The strategy options available for optimization within the analysis are:

- Access strategy (work boats, helicopter support, floatel, offshore base, Jack-Up as base and hovercraft support);
- Significant wave height (Hs) operational limits for work boats and daughter crafts (4 Hs capabilities available);
- Speed operational limits for work boats and daughter crafts (20 or 30 knots); and
- Repair crew resource (3 to 18 crews).

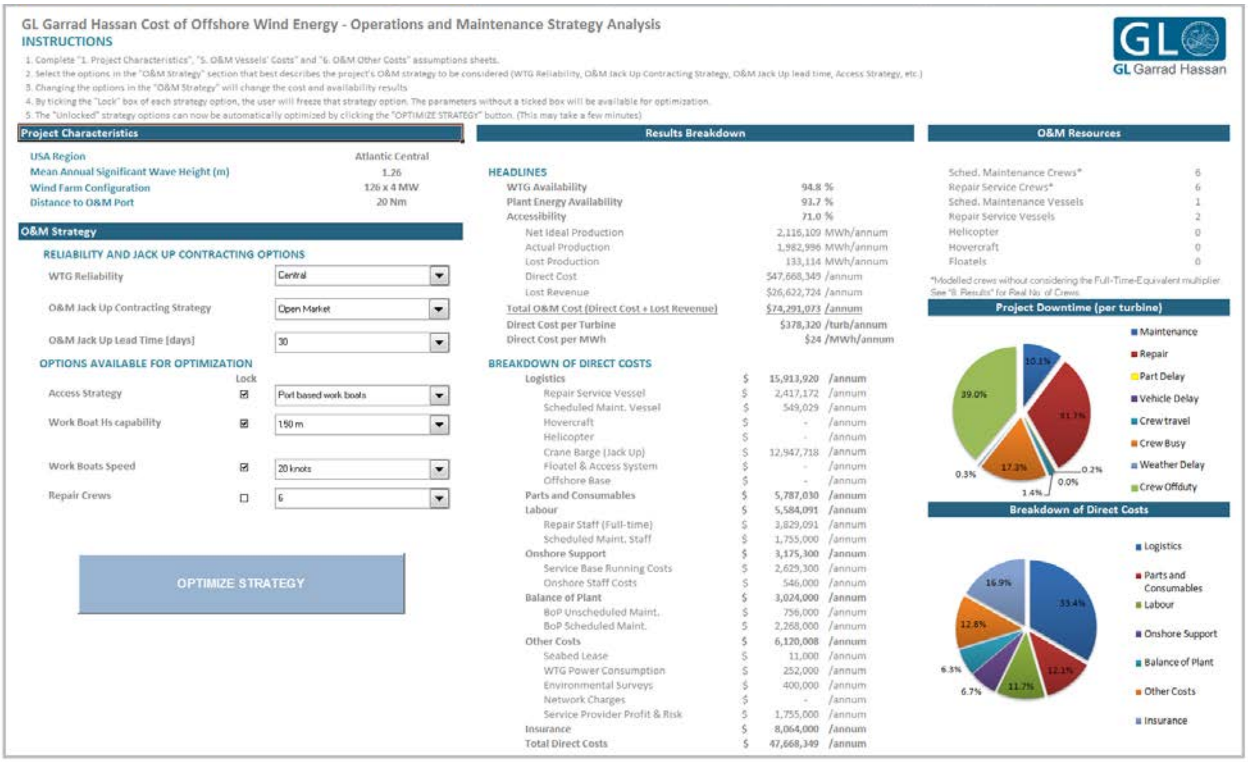
4) Optimization of the O&M Strategy is then performed by clicking on the “OPTIMIZE STRATEGY” button. There are two approaches that the User can take:

    i) **Optimal O&M Strategy considering all strategy options.** For this approach, un-tick all the boxes next to each of the strategy options and click “OPTIMIZE STRATEGY”. Because of the many different combinations that the Model evaluates, this process may take few minutes. When finished, the options dropdown menus will show the optimal O&M Strategy and the resources required for such strategy.

    ii) **Optimize one or certain specific strategy options.** When only interested in optimizing certain aspects of the O&M Strategy, the User must tick the boxes of the Strategy Options which are fixed to the project of interest and un-tick the boxes of the options to be optimized. Press the “OPTIMIZE STRATEGY” button. This process may take few minutes depending on the number of options to optimize. When finished, the options dropdown menus will show the optimal O&M Strategy and the resources required for such strategy.

Note: The Optimal O&M Strategy is project specific, therefore if changing: main project characteristics (except Foundation Type and Distance to Installation Port), Energy Production Parameters, O&M cost assumptions, Wind Turbine Reliability assumption, Jack-Up contracting strategy and/or the Jack-Up lead time options, the O&M strategy would require re-optimizing.

The user can view a breakdown of: the Total O&M Direct Costs, the resource requirements, and the causes of turbine downtime for the chosen strategy.



GL Garrad Hassan Cost of Offshore Wind Energy - Operations and Maintenance Strategy Analysis

INSTRUCTIONS

1. Complete "1. Project Characteristics", "5. O&M Vessels' Costs" and "6. O&M Other Costs" assumptions sheets.
2. Select the options in the "O&M Strategy" section that best describes the project's O&M strategy to be considered (WTG Reliability, O&M Jack Up Contracting Strategy, O&M Jack Up lead time, Access Strategy, etc.)
3. Changing the options in the "O&M Strategy" will change the cost and availability results
4. By ticking the "Lock" box of each strategy option, the user will freeze that strategy option. The parameters without a ticked box will be available for optimization.
5. The "Unlocked" strategy options can now be automatically optimized by clicking the "OPTIMIZE STRATEGY" button. (This may take a few minutes)

Project Characteristics

USA Region	Atlantic Central
Mean Annual Significant Wave Height (m)	1.26
Wind Farm Configuration	126 x 4 MW
Distance to O&M Port	20 Nm

O&M Strategy

RELIABILITY AND JACK UP CONTRACTING OPTIONS

WTG Reliability	Central
O&M Jack Up Contracting Strategy	Open Market
O&M Jack Up Lead Time [days]	30

OPTIONS AVAILABLE FOR OPTIMIZATION

	Lock	
Access Strategy	☑	Port based work boats
Work Boat Hs capability	☑	1.50 m
Work Boats Speed	☑	20 knots
Repair Crews	☐	6

Results Breakdown

HEADLINES

WTG Availability	94.8 %
Plant Energy Availability	93.7 %
Accessibility	71.0 %
Net Ideal Production	2,116,109 MWh/annum
Actual Production	1,982,996 MWh/annum
Lost Production	133,114 MWh/annum
Direct Cost	$47,668,349 /annum
Lost Revenue	$26,622,724 /annum
Total O&M Cost (Direct Cost + Lost Revenue)	$74,291,073 /annum
Direct Cost per Turbine	$378,320 /turb/annum
Direct Cost per MWh	$24 /MWh/annum

BREAKDOWN OF DIRECT COSTS

Logistics	$	15,913,920	/annum
Repair Service Vessel	$	2,417,172	/annum
Scheduled Maint. Vessel	$	549,029	/annum
Hovercraft	$	-	/annum
Helicopter	$	-	/annum
Crane Barge (Jack Up)	$	12,947,718	/annum
Floatel & Access System	$	-	/annum
Offshore Base	$	-	/annum
Parts and Consumables	$	5,787,030	/annum
Labour	$	5,584,091	/annum
Repair Staff (Full-time)	$	3,829,091	/annum
Scheduled Maint. Staff	$	1,755,000	/annum
Onshore Support	$	3,175,300	/annum
Service Base Running Costs	$	2,629,300	/annum
Onshore Staff Costs	$	546,000	/annum
Balance of Plant	$	3,024,000	/annum
BoP Unscheduled Maint.	$	756,000	/annum
BoP Scheduled Maint.	$	2,268,000	/annum
Other Costs	$	6,120,008	/annum
Seabed Lease	$	11,000	/annum
WTG Power Consumption	$	252,000	/annum
Environmental Surveys	$	400,000	/annum
Network Charges	$	-	/annum
Service Provider Profit & Risk	$	1,755,000	/annum
Insurance	$	8,064,000	/annum
Total Direct Costs	$	47,668,349	/annum

O&M Resources

Sched. Maintenance Crews*	6
Repair Service Crews*	6
Sched. Maintenance Vessels	1
Repair Service Vessels	2
Helicopter	0
Hovercraft	0
Floatels	0

*Modelled crews without considering the Full-Time-Equivalent multiplier. See "8. Results" for Real No. of Crews.

Project Downtime (per turbine)

Breakdown of Direct Costs

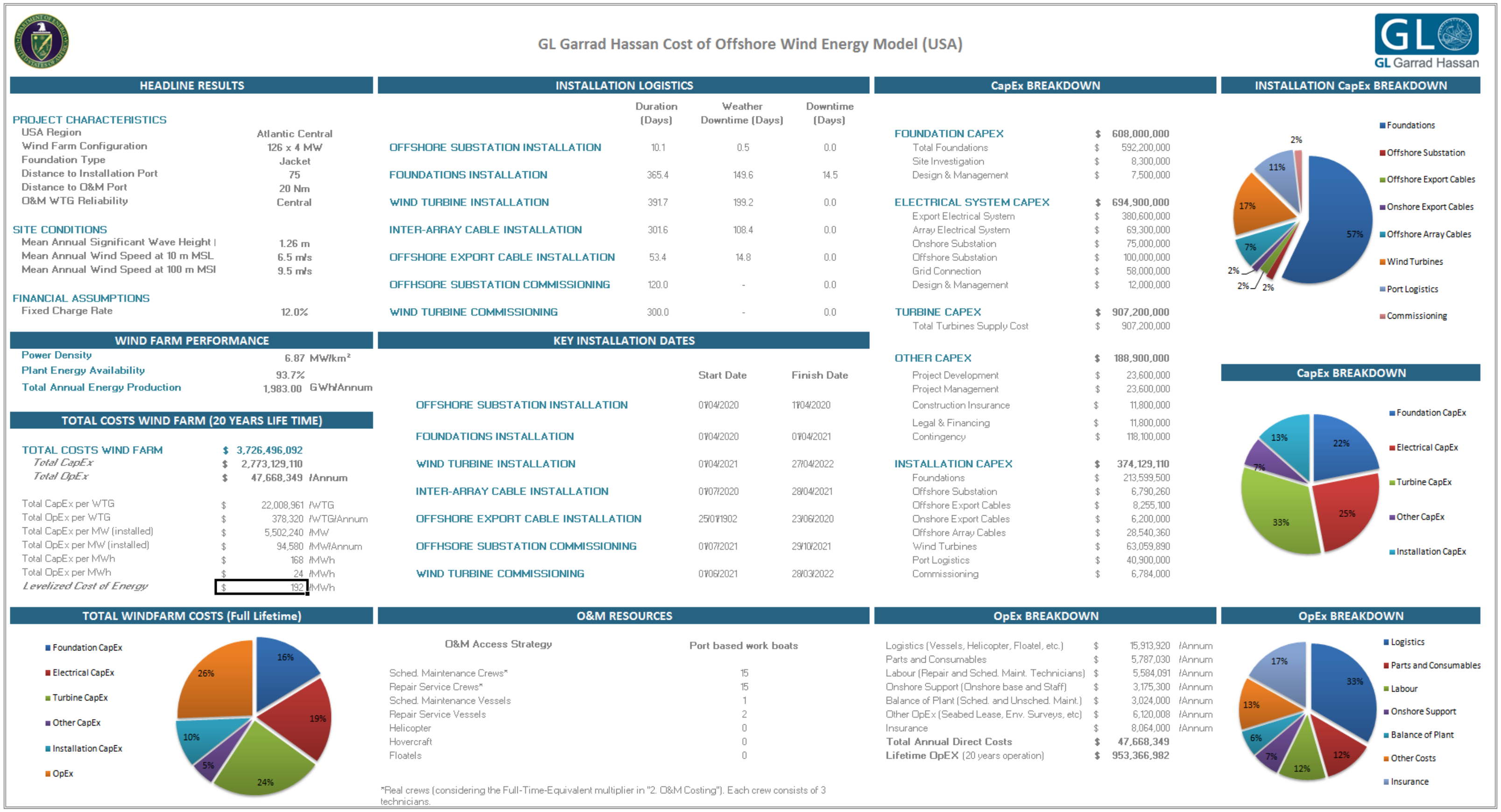
Figure A-11: O&M Analysis Sheet

"8. Results"

Review a summary of the costs and logistics of the installation and O&M of the project under consideration. The Results sheet presents a breakdown of resources and costs for both the installation and the operational phases of the project as well as the estimation of the Levelized Cost of Energy for the full project.

The Results sheet presents:

- A breakdown of the Installation Logistics required (operational duration, weather, logistic and vessel delays);
- A summary of the Key Installation Dates;
- A breakdown of the O&M Strategy Resources (access strategy, number of crews and vessels);
- A breakdown of the total costs of the wind farm (Installation CapEx, CapEx and OpEx);
- A breakdown of the Installation CapEx (Foundations, Offshore substation, Export Cables, Wind Turbines, etc);
- A breakdown of the Capital Expenditure (CapEx excluding installation costs);
- A breakdown of the Operational Expenditure (OpEx); and
- The Levelized Cost of Energy for the analyzed scenario.



GL Garrad Hassan Cost of Offshore Wind Energy Model (USA)

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HEADLINE RESULTS

PROJECT CHARACTERISTICS

USA Region	Atlantic Central
Wind Farm Configuration	126 x 4 MW
Foundation Type	Jacket
Distance to Installation Port	75
Distance to O&M Port	20 Nm
O&M WTG Reliability	Central

SITE CONDITIONS

Mean Annual Significant Wave Height |	1.26 m
Mean Annual Wind Speed at 10 m MSL	6.5 m/s
Mean Annual Wind Speed at 100 m MSl	9.5 m/s

FINANCIAL ASSUMPTIONS

Fixed Charge Rate	12.0%

WIND FARM PERFORMANCE

Power Density	6.87	MW/km²
Plant Energy Availability	93.7%	
Total Annual Energy Production	1,983.00	GWh/Annum

TOTAL COSTS WIND FARM (20 YEARS LIFE TIME)

TOTAL COSTS WIND FARM	$	3,726,496,092	
Total CapEx	$	2,773,129,110	
Total OpEx	$	47,668,349	/Annum
Total CapEx per WTG	$	22,008,961	/WTG
Total OpEx per WTG	$	378,320	/WTG/Annum
Total CapEx per MW (installed)	$	5,502,240	/MW
Total OpEx per MW (installed)	$	94,580	/MW/Annum
Total CapEx per MWh	$	168	/MWh
Total OpEx per MWh	$	24	/MWh
Levelized Cost of Energy	$	192	/MWh

INSTALLATION LOGISTICS

	Duration (Days)	Weather Downtime (Days)	Downtime (Days)
OFFSHORE SUBSTATION INSTALLATION	10.1	0.5	0.0
FOUNDATIONS INSTALLATION	365.4	149.6	14.5
WIND TURBINE INSTALLATION	391.7	199.2	0.0
INTER-ARRAY CABLE INSTALLATION	301.6	108.4	0.0
OFFSHORE EXPORT CABLE INSTALLATION	53.4	14.8	0.0
OFFHSORE SUBSTATION COMMISSIONING	120.0	-	0.0
WIND TURBINE COMMISSIONING	300.0	-	0.0

KEY INSTALLATION DATES

	Start Date	Finish Date
OFFSHORE SUBSTATION INSTALLATION	01/04/2020	11/04/2020
FOUNDATIONS INSTALLATION	01/04/2020	01/04/2021
WIND TURBINE INSTALLATION	01/04/2021	27/04/2022
INTER-ARRAY CABLE INSTALLATION	01/07/2020	28/04/2021
OFFSHORE EXPORT CABLE INSTALLATION	25/01/1902	23/06/2020
OFFHSORE SUBSTATION COMMISSIONING	01/07/2021	29/10/2021
WIND TURBINE COMMISSIONING	01/06/2021	28/03/2022

CapEx BREAKDOWN

FOUNDATION CAPEX	$	608,000,000
Total Foundations	$	592,200,000
Site Investigation	$	8,300,000
Design & Management	$	7,500,000
ELECTRICAL SYSTEM CAPEX	$	694,900,000
Export Electrical System	$	380,600,000
Array Electrical System	$	69,300,000
Onshore Substation	$	75,000,000
Offshore Substation	$	100,000,000
Grid Connection	$	58,000,000
Design & Management	$	12,000,000
TURBINE CAPEX	$	907,200,000
Total Turbines Supply Cost	$	907,200,000
OTHER CAPEX	$	188,900,000
Project Development	$	23,600,000
Project Management	$	23,600,000
Construction Insurance	$	11,800,000
Legal & Financing	$	11,800,000
Contingency	$	118,100,000
INSTALLATION CAPEX	$	374,129,110
Foundations	$	213,599,500
Offshore Substation	$	6,790,260
Offshore Export Cables	$	8,255,100
Onshore Export Cables	$	6,200,000
Offshore Array Cables	$	28,540,360
Wind Turbines	$	63,059,890
Port Logistics	$	40,900,000
Commissioning	$	6,784,000

INSTALLATION CapEx BREAKDOWN

CapEx BREAKDOWN

TOTAL WINDFARM COSTS (Full Lifetime)

O&M RESOURCES

O&M Access Strategy	Port based work boats
Sched. Maintenance Crews*	15
Repair Service Crews*	15
Sched. Maintenance Vessels	1
Repair Service Vessels	2
Helicopter	0
Hovercraft	0
Floatels	0

*Real crews (considering the Full-Time-Equivalent multiplier in "2. O&M Costing"). Each crew consists of 3 technicians.

OpEx BREAKDOWN

Logistics (Vessels, Helicopter, Floatel, etc.)	$	15,913,920	/Annum
Parts and Consumables	$	5,787,030	/Annum
Labour (Repair and Sched. Maint. Technicians)	$	5,584,091	/Annum
Onshore Support (Onshore base and Staff)	$	3,175,300	/Annum
Balance of Plant (Sched. and Unsched. Maint.)	$	3,024,000	/Annum
Other OpEx (Seabed Lease, Env. Surveys, etc)	$	6,120,008	/Annum
Insurance	$	8,064,000	/Annum
Total Annual Direct Costs	$	47,668,349	
Lifetime OpEX (20 years operation)	$	953,366,982	

OpEx BREAKDOWN

Figure A-12: Cost of Offshore Wind Energy Model Results

APPENDIX B NET ENERGY PRODUCTION RESULTS

Table B-1: Energy Production Results for each Wind Climate – Atlantic North

	Wind Climate at Hub Height	6.6 m/s			8.4 m/s			10.2 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,395,576	1,395,576	1,395,576	2,129,778	2,129,778	2,129,778	2,676,366	2,676,366	2,676,366	GWh/annum
	Wake Loss Efficiency	83.1	86.9	89.6	87.8	90.6	92.6	90.9	93.0	94.5	%
	Net Energy Output	1,159,951	1,212,284	1,250,045	1,869,880	1,930,248	1,972,891	2,431,717	2,489,407	2,529,742	GWh/annum
	Estimated Capacity Factor [2]	26.3	27.4	28.3	42.3	43.7	44.7	55.0	56.3	57.3	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,463,448	1,463,448	1,463,448	2,200,548	2,200,548	2,200,548	2,740,332	2,740,332	2,740,332	GWh/annum
	Wake Loss Efficiency	85.4	88.9	91.4	89.3	92.0	93.8	92.2	94.1	95.5	%
	Net Energy Output	1,249,091	1,300,906	1,337,366	1,965,145	2,023,855	2,064,496	2,525,217	2,579,807	2,617,144	GWh/annum
	Estimated Capacity Factor [2]	28.3	29.4	30.3	44.5	45.8	46.7	57.2	58.4	59.2	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-2: Energy Production Results for each Wind Climate – Atlantic Central

	Wind Climate at Hub Height	6.6 m/s			8.4 m/s			10.2 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,399,482	1,399,482	1,399,482	2,149,560	2,149,560	2,149,560	2,703,204	2,703,204	2,703,204	GWh/annum
	Wake Loss Efficiency	82.8	86.6	89.4	87.4	90.3	92.4	91.0	93.1	94.6	%
	Net Energy Output	1,158,986	1,212,520	1,250,924	1,879,368	1,941,789	1,986,000	2,459,058	2,516,720	2,557,197	GWh/annum
	Estimated Capacity Factor [2]	26.2	27.4	28.3	42.5	44.0	45.0	55.7	57.0	57.9	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,469,244	1,469,244	1,469,244	2,221,632	2,221,632	2,221,632	2,766,288	2,766,288	2,766,288	GWh/annum
	Wake Loss Efficiency	85.1	88.7	91.2	89.2	91.9	93.8	92.3	94.3	95.6	%
	Net Energy Output	1,249,730	1,302,887	1,340,078	1,982,535	2,042,286	2,083,642	2,553,264	2,607,423	2,644,616	GWh/annum
	Estimated Capacity Factor [2]	28.3	29.5	30.3	44.9	46.2	47.2	57.8	59.0	59.9	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-3: Energy Production Results for each Wind Climate – Atlantic South

	Wind Climate at Hub Height	6.6 m/s			8.4 m/s			10.2 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,370,628	1,370,628	1,370,628	2,161,152	2,161,152	2,161,152	2,767,338	2,767,338	2,767,338	GWh/annum
	Wake Loss Efficiency	82.4	86.3	89.1	86.7	89.7	91.9	90.3	92.6	94.2	%
	Net Energy Output	1,128,837	1,182,289	1,220,697	1,872,778	1,938,895	1,985,767	2,499,850	2,563,127	2,607,395	GWh/annum
	Estimated Capacity Factor [2]	25.6	26.8	27.6	42.4	43.9	44.9	56.6	58.0	59.0	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,442,280	1,442,280	1,442,280	2,240,028	2,240,028	2,240,028	2,835,924	2,835,924	2,835,924	GWh/annum
	Wake Loss Efficiency	84.6	88.3	90.9	88.5	91.4	93.4	91.8	93.9	95.3	%
	Net Energy Output	1,220,557	1,273,941	1,311,350	1,983,085	2,046,901	2,091,067	2,602,567	2,662,011	2,702,682	GWh/annum
	Estimated Capacity Factor [2]	27.6	28.8	29.7	44.9	46.3	47.3	58.9	60.3	61.2	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-4: Energy Production Results for each Wind Climate – Gulf of Mexico East

	Wind Climate at Hub Height	6.8 m/s			8.5 m/s			10.2 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,491,210	1,491,210	1,491,210	2,186,604	2,186,604	2,186,604	2,710,638	2,710,638	2,710,638	GWh/annum
	Wake Loss Efficiency	83.4	87.1	89.8	87.4	90.3	92.4	90.8	92.9	94.5	%
	Net Energy Output	1,243,896	1,299,187	1,338,727	1,912,169	1,975,489	2,020,372	2,460,248	2,519,334	2,560,881	GWh/annum
	Estimated Capacity Factor [2]	28.2	29.4	30.3	43.3	44.7	45.7	55.7	57.0	58.0	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,563,156	1,563,156	1,563,156	2,260,524	2,260,524	2,260,524	2,775,612	2,775,612	2,775,612	GWh/annum
	Wake Loss Efficiency	85.6	89.1	91.6	89.3	92.0	93.8	92.2	94.1	95.5	%
	Net Energy Output	1,338,272	1,392,944	1,431,089	2,018,172	2,078,723	2,120,647	2,557,813	2,613,208	2,651,287	GWh/annum
	Estimated Capacity Factor [2]	30.3	31.5	32.4	45.7	47.1	48.0	57.9	59.1	60.0	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-5: Energy Production Results for each Wind Climate – Gulf of Mexico West

	Wind Climate at Hub Height	6.8 m/s			8.5 m/s			10.2 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,484,154	1,484,154	1,484,154	2,223,900	2,223,900	2,223,900	2,789,388	2,789,388	2,789,388	GWh/annum
	Wake Loss Efficiency	82.2	86.2	89.0	86.5	89.7	91.9	90.2	92.6	94.2	%
	Net Energy Output	1,220,054	1,279,116	1,320,874	1,924,679	1,994,130	2,042,841	2,516,655	2,581,597	2,626,820	GWh/annum
	Estimated Capacity Factor [2]	27.6	29.0	29.9	43.6	45.1	46.2	57.0	58.4	59.5	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,560,636	1,560,636	1,560,636	2,303,280	2,303,280	2,303,280	2,858,268	2,858,268	2,858,268	GWh/annum
	Wake Loss Efficiency	84.4	88.2	90.8	88.4	91.3	93.3	91.7	93.8	95.3	%
	Net Energy Output	1,316,682	1,375,815	1,416,725	2,036,481	2,103,349	2,149,203	2,620,244	2,681,179	2,722,732	GWh/annum
	Estimated Capacity Factor [2]	29.8	31.1	32.1	46.1	47.6	48.6	59.3	60.7	61.6	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-6: Energy Production Results for each Wind Climate – Pacific South

	Wind Climate at Hub Height	6.8 m/s			8.1 m/s			9.4 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,541,484	1,541,484	1,541,484	2,066,274	2,066,274	2,066,274	2,478,042	2,478,042	2,478,042	GWh/annum
	Wake Loss Efficiency	83.0	86.9	89.6	87.0	90.1	92.2	90.0	92.4	94.0	%
	Net Energy Output	1,279,898	1,340,061	1,381,826	1,797,617	1,861,431	1,905,227	2,229,298	2,289,103	2,329,978	GWh/annum
	Estimated Capacity Factor [2]	29.0	30.3	31.3	40.7	42.1	43.1	50.5	51.8	52.7	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,612,464	1,612,464	1,612,464	2,134,356	2,134,356	2,134,356	2,539,740	2,539,740	2,539,740	GWh/annum
	Wake Loss Efficiency	85.2	88.8	91.4	88.8	91.6	93.6	91.3	93.6	95.1	%
	Net Energy Output	1,373,090	1,432,529	1,473,013	1,894,453	1,955,588	1,996,825	2,319,908	2,376,478	2,414,512	GWh/annum
	Estimated Capacity Factor [2]	31.1	32.4	33.3	42.9	44.3	45.2	52.5	53.8	54.7	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-7: Energy Production Results for each Wind Climate – Pacific North

	Wind Climate at Hub Height	6.8 m/s			8.1 m/s			9.4 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,472,940	1,472,940	1,472,940	2,006,676	2,006,676	2,006,676	2,448,054	2,448,054	2,448,054	GWh/annum
	Wake Loss Efficiency	83.2	87.1	89.7	86.0	89.3	91.5	88.8	91.5	93.3	%
	Net Energy Output	1,226,176	1,282,624	1,321,309	1,726,718	1,792,218	1,836,824	2,175,084	2,240,469	2,284,811	GWh/annum
	Estimated Capacity Factor [2]	27.8	29.0	29.9	39.1	40.6	41.6	49.2	50.7	51.7	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,542,576	1,542,576	1,542,576	2,081,268	2,081,268	2,081,268	2,517,228	2,517,228	2,517,228	GWh/annum
	Wake Loss Efficiency	85.1	88.8	91.2	87.7	90.8	92.9	90.3	92.8	94.5	%
	Net Energy Output	1,312,389	1,369,098	1,407,315	1,825,858	1,890,089	1,933,100	2,273,441	2,335,966	2,377,659	GWh/annum
	Estimated Capacity Factor [2]	29.7	31.0	31.9	41.3	42.8	43.8	51.5	52.9	53.8	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

Table B-8: Energy Production Results for each Wind Climate – Great Lakes

	Wind Climate at Hub Height	7.4 m/s			8.1 m/s			8.8 m/s			Units
Turbine Capacity	Layout Spacing	8 D	10 D	12 D	8 D	10 D	12 D	8 D	10 D	12 D	(Diameters)
4 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,735,902	1,735,902	1,735,902	1,972,530	1,972,530	1,972,530	2,182,068	2,182,068	2,182,068	GWh/annum
	Wake Loss Efficiency	86.7	89.7	91.9	88.0	90.8	92.7	89.3	91.8	93.5	%
	Net Energy Output	1,504,202	1,557,901	1,595,061	1,735,963	1,791,315	1,829,430	1,947,950	2,003,101	2,040,930	GWh/annum
	Estimated Capacity Factor [2]	34.0	35.3	36.1	39.3	40.5	41.4	44.1	45.3	46.2	%
6 MW	Wind Farm Rated Power [1]	504	504	504	504	504	504	504	504	504	MW
	Ideal Energy Output	1,799,196	1,799,196	1,799,196	2,035,992	2,035,992	2,035,992	2,244,228	2,244,228	2,244,228	GWh/annum
	Wake Loss Efficiency	88.4	91.3	93.3	89.6	92.2	94.0	90.7	93.1	94.6	%
	Net Energy Output	1,590,257	1,642,457	1,677,838	1,824,147	1,877,549	1,913,575	2,035,525	2,088,428	2,123,984	GWh/annum
	Estimated Capacity Factor [2]	36.0	37.2	38.0	41.3	42.5	43.3	46.1	47.3	48.1	%

1. This value is based on the nameplate rated power rather than the peak power of the power curve assumed.
2. Assuming internal wake losses only, no other losses considered.

APPENDIX C WIND AND WAVE DATA SOURCE LOCATIONS AND ICE COVERAGE PLOTS

1. Locations of Sub-regions and Data Buoys for Metocean Data

The boundaries of Sub-regions 1 to 8 (denoted by blue lines) and the positions of measured data (denoted by red dots and associated reference numbers) are illustrated in Figure C-1 to Figure C-8.

Figure C-1: Boundary of Atlantic North Region and Selected Locations

Figure C-2: Boundary of Atlantic Central Region and Selected Locations

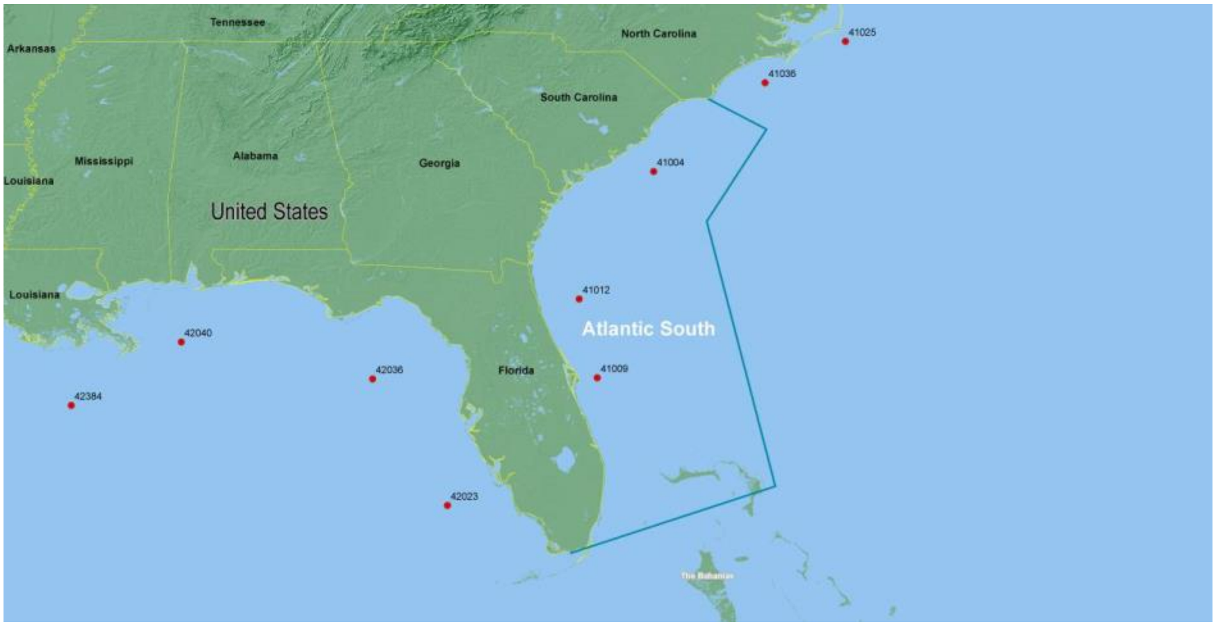

Figure C-3: Boundary of Atlantic South Region and Selected Locations

Figure C-4: Boundary of Gulf of Mexico East and Selected Locations

Figure C-5: Boundary of Gulf of Mexico West Region and Selected Locations

Figure C-6: Boundary of Pacific North Region and Selected Locations

Figure C-7: Boundary of Pacific South Region and Selected Locations

Figure C-8: Boundary of Great Lakes Region and Selected Locations

2. Plots of Ice Coverage within the Great Lakes

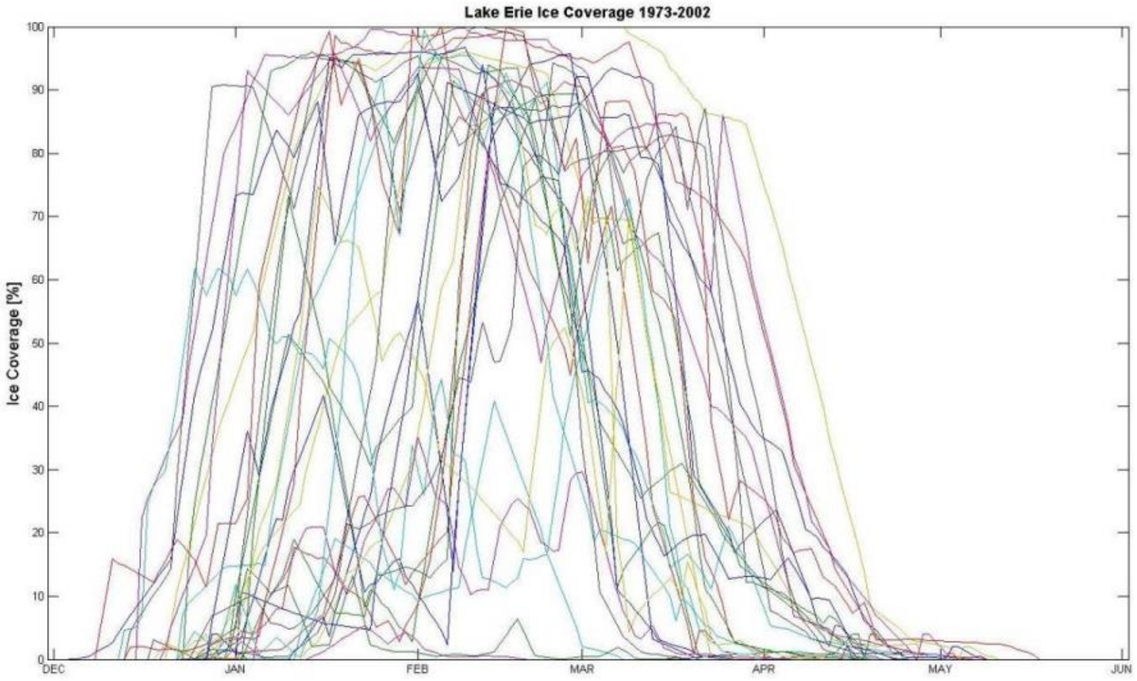

Figure C-9: Lake Erie Ice Coverage between 1973 and 2002

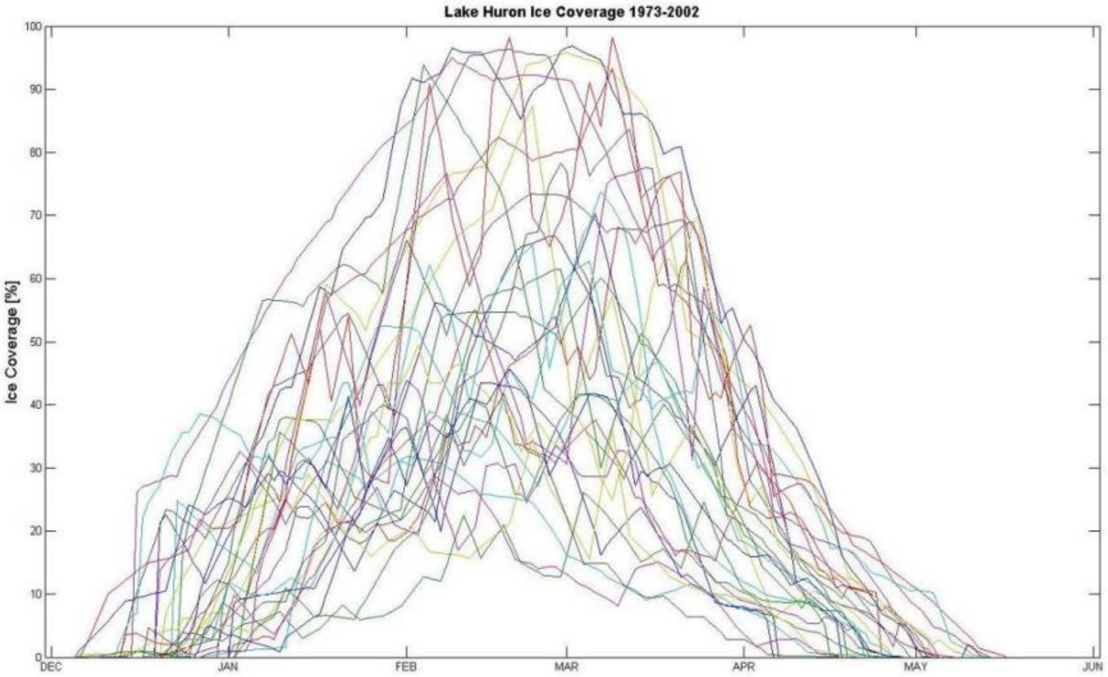

Figure C-10: Lake Huron Ice Coverage between 1973 and 2002

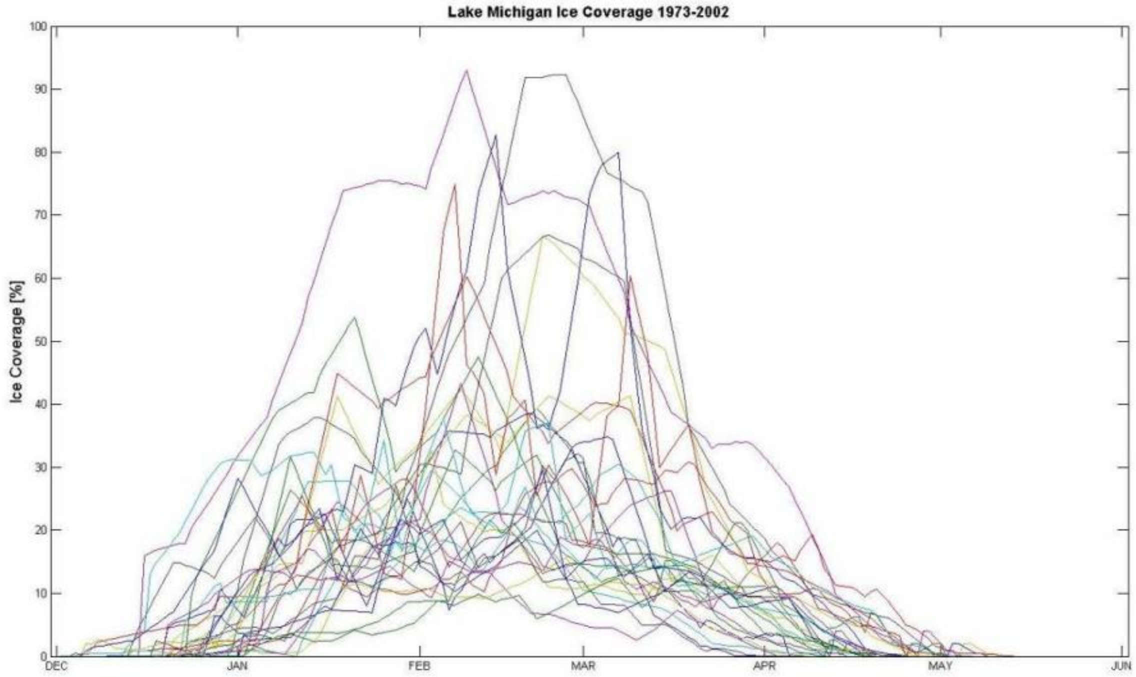

Figure C-11: Lake Michigan Ice Coverage between 1973 and 2002

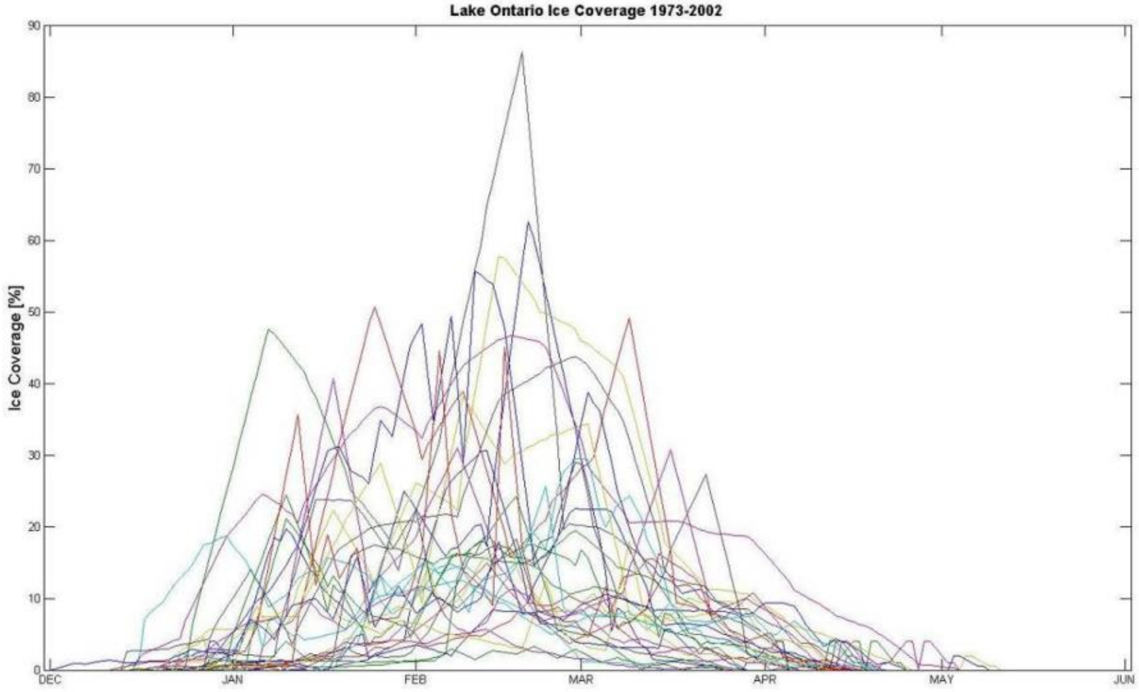

Figure C-12: Lake Ontario Ice Coverage between 1973 and 2002

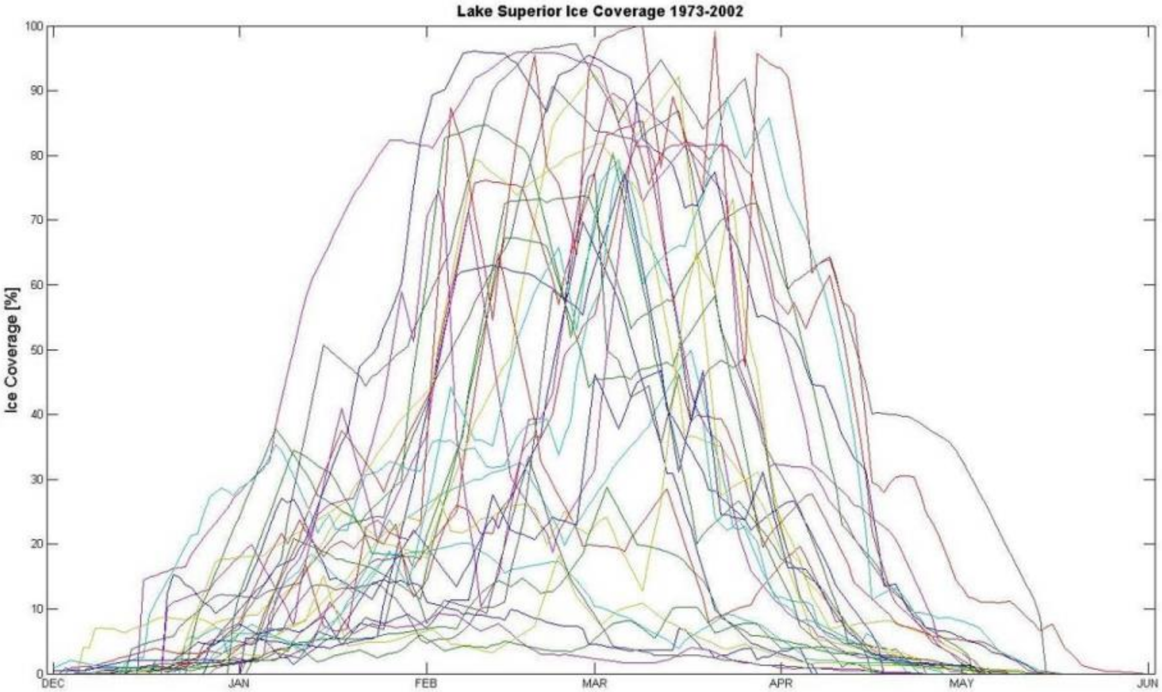

Figure C-13: Lake Superior Ice Coverage between 1973 and 2002