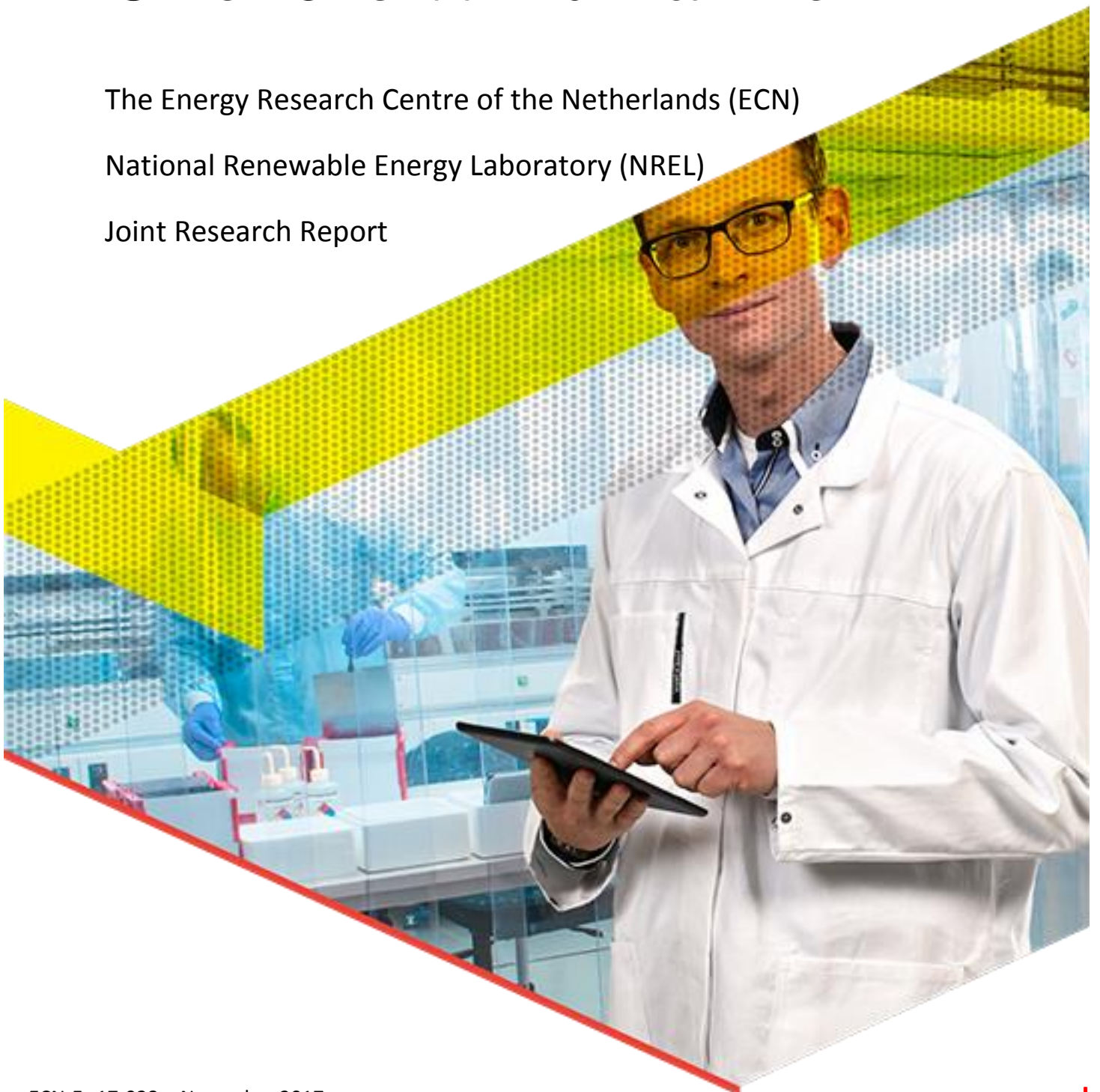


Operation and Maintenance Map of U.S. Offshore Wind Farms

The Energy Research Centre of the Netherlands (ECN)

National Renewable Energy Laboratory (NREL)

Joint Research Report



Operation and Maintenance Map of U.S. Offshore Wind Farms

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Executive Summary

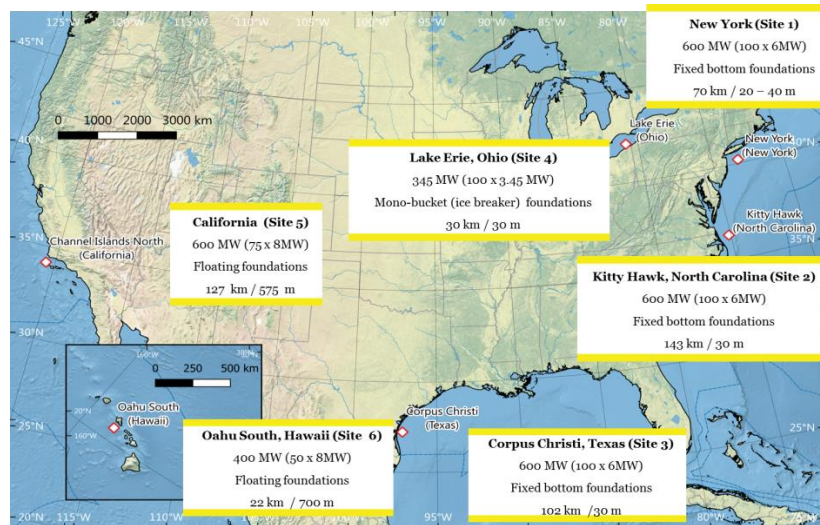
The global commitment to reduce the use of fossil fuel has pushed the development of sustainable energy sources. One sustainable energy technology that has arisen in the past few decades is wind energy. Currently, the onshore wind market has established itself as an integral part of the energy mix globally, especially in China, Europe, and the United States. As the need for carbon-free electricity grows, the offshore wind market is expected to follow. The opportunity for offshore wind energy has recently been bolstered by the emergence of floating turbine demonstration projects for installing turbines in deep-water locations, further increasing offshore wind's potential. At present, nearly 88% of the current total offshore-wind-energy installed capacity (12.6 GW) is located in waters off the coast of 10 European countries [1]. On the other hand, the United States has recently installed its first offshore wind farm—the Block Island Wind Farm off the coast of Block Island, Rhode Island—and the U.S. offshore wind market has an estimated pipeline of 24 GW of projects in development [2]. Many states in the U.S. have begun looking towards the offshore market with great interest and exploring its overall value chain.

Operation and maintenance (O&M) is a vital part of an offshore wind farm's life-cycle cost, contributing 25%-30% of the overall levelized cost of energy (LCOE). Because every wind farm has a unique set of site characteristics, each requires a dedicated O&M strategy. Hence, a thorough investigation of the most suitable O&M strategy for a wind farm should be performed both at the planning and operational phases. In this report, researchers from the Energy Research Centre of the Netherlands (ECN) and the National Renewable Energy Laboratory (NREL) aim to evaluate the most suitable strategy for six prospective offshore wind farms in the United States by using ECN's O&M calculator. For this analysis different vessel mixes are assessed: crew transfer vessels (CTV) with different operation limits, surface effect ships (SES), service operation vessels (SOV), and helicopters are considered. A strategy is selected as most suitable if it results in more than 95% or higher availability (percentage of yield and time) among the strategies and is the lowest operation expenditure (OPEX) (c\$/kWh). Numerous parameters affect the strategy selection, including wind farm characteristics, component failure rates, resource availability and costs, and local electricity prices.

Six prospective wind farm sites in the United States (shown in Figure 1) are selected for this study. These sites are located off the coast of New York (site 1), North Carolina (site 2), Texas (site 3), Ohio (site 4), California (site 5), and Hawaii (site 6). The capacity of the wind farms range from

345–600 MW. As shown in Figure 1, these sites represent near-shore (site 4,6), far-shore (site 1,2,3,5), shallow-water (site 1,2,3,4), and deep-water (site 5,6) conditions.

Figure 1: Six reference wind farms selected for the O&M case study



The results show that near-shore sites like the Ohio or Hawaii sites are most cost-effectively maintained by multiple crew transfer vessels (CTVs). On the other hand, far-shore sites—namely New York, North Carolina, Texas, and Pacific sites—require vessels with higher operational limitations (e.g., maximum wind speed and wave height) such as surface effect ships (SES) or service operation vessel (SOV). To replace large components, jack-up barges are used in shallow waters with fixed-bottom-foundation turbines, while towing vessels are used to bring turbines with floating foundations to shore at the deep-water sites. The OPEX of these wind farms range from 1.31 – 4.37 c\$/kWh. A summary of results is shown in Table 1.

Table 1: Summary of the O&M Key Performance Indicators of the Chosen Strategies

Sites	Name of the Site	Characteristics	Most suitable strategy	Time-based Availability (%)	Yield-based Availability (%)	Cost per kWh (c\$/kWh)	Total O&M Cost (M\$/year)
1	New York	600 MW (100*6 MW) 70 km from Leonardo State Marina Harbour; 20-40 m deep	SES	95.1	94.8	1.94	55.56
2	North Carolina	600 MW (100*6 MW) 143 km from Newport News Harbor; 300 m deep	SOV	95.7	95.8	2.33	53.93
3	Texas	600 MW (100*6 MW) 102 km from Corpus Christi Harbor; 25 m deep	SES	95.3	95.3	1.82	50.86
4	Ohio	345 MW (100*3.45 MW) 32 km from Ashtabula Harbor; 22 m deep	CTV & Helicopter	93.3	92.9	4.37	45.62
5	California	600 MW (75*8 MW) 127 km from Hueneme Harbour; 575 m deep	SOV	95.2	95	1.31	45.94
6	Hawaii	400 MW (50*8 MW) 38 km from Honolulu Harbour; 700 m deep	CTV +	95.8	95.7	1.35	41.49

In this study, two unique challenges for offshore wind specific to the United States are considered and evaluated including weather conditions and vessel availability. The first challenge is the

potential for hurricanes or tropical storms to occur on the East Coast and the Gulf of Mexico. For this analysis, the impact of hurricanes on O&M costs are assessed by assuming that prospective wind farms in hurricane regions have an increase in failure rates for exterior turbine components of 20%. As a result, the cost per kilowatt hour increases by approximately 5%. For prospective offshore wind projects in fresh water environments such as the Great Lakes, ice may be present and is expected to impact the O&M costs. This study shows that using a helicopter during icing periods can increase the time-based availability by 2.7%.

Additionally, the United States has a federal statute in place, known as The Merchant Marine Act of 1920 (or the Jones Act), to promote and maintain U.S. marine operation activities. In general, the Jones Act forbids any foreign-flagged vessel from engaging in coastwise trade within the United States. This introduces a challenge for offshore wind in the since currently there are no U.S.-flagged vessels for large-turbine-component replacement such as heavy-lift jack-up barges with high lift heights. In large component repair situations where the lift height and capacity exceeds those of existing U.S. vessels, the prospective U.S. wind farm requires charter of a foreign-flagged vessel (from Europe in this study). Therefore, the replacement vessels would arrive from Europe whenever large replacements were required. The study shows that chartering foreign-flagged heavy-lift jack-up barges from Europe leads to approximately 28% higher O&M costs (evaluated on the most suitable strategy of site 2) than if the replacement is conducted by theoretical U.S.-built vessels.

In this study, a comparison between Europe and the United States is also performed. When assessing the prospective offshore wind farms with Europe we see an 18%-20% difference in the repair cost between two similar wind farms in the United States and Europe. The driving factors for this difference are the inherent site characteristics and metocean conditions of the United States compared to those of an offshore wind project in the North Sea as well as the lack of a U.S. supply chain and U.S.-flagged vessels capable of conducting large repairs. However, if the most suitable strategy is chosen and a U.S vessel fleet is available then the O&M repair cost difference is only 1%–1.5% (with the cost being higher in the United States) for similar sites in Europe and in the United States. In this study, the comparison example is between the Gemini wind farm in Europe and the New York or Texas sites.

1. Introduction



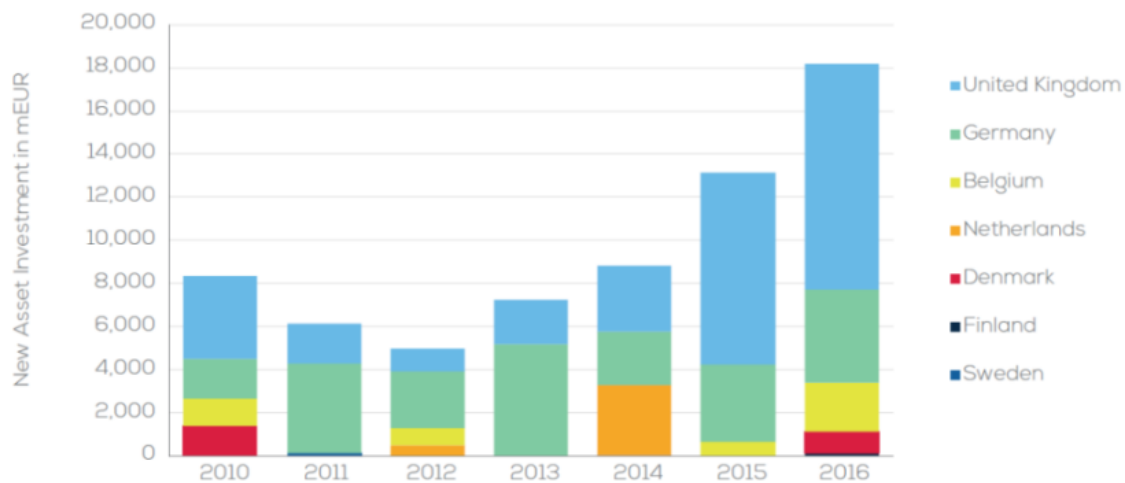
According to the *National Offshore Wind Strategy*, a report by the U.S. Department of Energy (DOE) and U.S. Department of Interior (DOI), offshore wind energy holds the promise of significant environmental and economic benefits for the United States. It is an abundant, low-carbon, domestic energy resource. The United States has started to develop offshore wind farms that could produce energy at low, long-term fixed costs, which can reduce electricity prices and improve energy security by providing a hedge against fossil fuel price volatility [3]. This report gives an overview of different U.S. prospective wind farms, each with varying characteristics and challenges. This report also evaluates different O&M strategies and their impacts to O&M Key Performance Indicators KPIs on these select wind farms.

1.1 Background

According to the Global Wind Energy Council, in 2016, the total installed wind energy capacity globally was 487 GW of which 14 GW are offshore wind farms. Nearly 88% (12,6 GW) are installed in waters off the coast of 10 European countries. The rest are located mainly in China, followed by Japan, South Korea, and the United States [4]. According to the Wind Europe report in 2016, 11 offshore projects are under construction which will add 4.8 GW capacity to the European grid [5]. This global trend shows that offshore wind farms are expected to continue to be promoted and developed as one of the core technologies that can generate clean and renewable energy.

The introduction of taller and bigger turbines is one of the major developments in the wind energy industry. One example is the successful completion of the installation of 8-MW wind turbines in Burbo Bank, United Kingdom. Furthermore, the average wind farm size has increased from around 80 MW in 2009 to 380 MW at present [5]. Trends also show market growth and technology advancement for deeper water and wind farms that are a further distance from shore. Therefore, more and more sites, that were previously inaccessible or in water that is too deep, have become potential sites for offshore wind energy. To strengthen aforementioned statements, from 2011 to 2016, the investment in European offshore wind farms tripled. Figure 2 shows the share of these investments.

Figure 2: New investment in European offshore wind farms (2010–2016)



1.2 O&M of Offshore Wind Farms

The development of an offshore wind farm requires capital expenditure (CAPEX), which includes not only infrastructure, manufacturing, and installation but also operational costs throughout the wind farm's lifetime. These operational and maintenance costs account for approximately 25% of plant LCOE over the lifetime of the facility (around 20-25 years). During this operational time, the main customers or the players for O&M services are project owners, original equipment manufacturers, and the electricity transmission connection owners [6].

O&M of an offshore wind farm involves a diverse range of activities. In principle, there are two KPIs on which the wind farm performance is measured and considered:

- Availability: a measure of the proportion of the time a wind farm is able to generate electricity.
- Operation expenditure: expenses incurred during the windfarm's operations phase

Ultimately, the goal of a wind farm service provider is to achieve higher availability at the lowest cost possible. The challenge is being able to combine higher availability with a cost-effective O&M strategy.

Two key elements are taken into consideration when evaluating these KPIs: maintenance actions and accessibility. Maintenance actions are the basic activities needed for the machine to run efficiently and produce energy. These actions could be carried out unscheduled/ad-hoc or scheduled based on regular service or condition- or health-based maintenance. Accessibility to the wind farm, on the other hand, is influenced by weather and sea conditions. Parameters, like wind speed, significant wave height, currents, and wave periods determine the accessibility of the vessels and technicians to the wind turbines. Accessibility is also constrained by the ability of the vessels to transfer technicians to the turbines. Additionally, the availability of the resources—vessels, technicians, tools, and spare parts—influence the overall KPIs [6].

As mentioned earlier, the challenge of the offshore industry is to continuously lower the operational cost. The highest portion of O&M costs is caused by the unplanned corrective

maintenance that needs to be conducted as the result of a component failure. This can lead to a long delay, with the wind farm not always accessible because of bad weather and the lack of resources required. Moreover, the O&M costs include not only the direct O&M repair costs but also the loss of revenue because of nonproducing wind turbines. Therefore, optimizing the O&M strategy is an important task needed to achieve and improve the targeted KPIs during the operational period.

One of the solutions to reducing the failure potential of a wind turbine's components is using a proactive maintenance approach. Proactive maintenance can be broadly categorized as calendar- and condition-based maintenance. Calendar-based maintenance is usually carried out at established time intervals or a number of units of used but without prior item condition investigation. On the other hand, condition-based maintenance relies on performance and parameters to monitor the subsequent actions. This type of maintenance can be a follow up from calendar-based maintenance or can be detected by various sensors.

1.3 U.S. Offshore Wind Farms

The U.S. offshore wind industry has experienced significant progress in recent years, with a general upturn in its outlook for sustained market growth since the *2014–2015 Offshore Wind Technologies Market Report* was released in September 2015 [7]. Most notably, in December 2016, Deepwater Wind's 30-MW Block Island Wind Farm became the first commercial offshore wind facility commissioned in the United States. This milestone was also accompanied by increasing domestic policy support in states such as Massachusetts, New York, and Maryland to attract offshore wind, as well as dramatic and demonstrative cost declines in European offshore wind markets. In September 2016, the *National Offshore Wind Strategy* [8] identified key research actions that would be needed to achieve the U.S. Department of Energy's *Wind Vision* deployment scenario of 86 GW of offshore wind by 2050 [9]. This information, in addition to more detailed information on the U.S. offshore wind industry, is provided by the *2016 Offshore Wind Technologies Market Report* [10].

1.4 O&M Modelling Tool

ECN is a market leader, developer, and owner of the industry-standard O&M strategy modeling tools designed especially for offshore wind. These tools have been validated by GL (Germanischer Lloyd) and used for nearly 15 years. ECN provides consultancy and licenses and has a customer base (O&M) of more than 30 of the offshore wind energy related industry's leading companies, which include nearly all of the developers and wind turbine manufacturers that are currently active in the offshore wind sector.

For this study, the ECN O&M Calculator was used to model different O&M strategies and to compute the corresponding O&M KPIs. The ECN O&M Calculator is a time-domain simulation program that enables offshore wind farms, developers, and operators to have a fair estimation of O&M costs (depending on the equipment and wind farm characteristics chosen). The main outputs provided are the availability in time (%) and in yield (%), the revenue losses (M\$/year), the repair costs (M\$/year), the cost per kWh (c\$/kWh), and the total O&M costs (M\$/year). Nevertheless, other output parameters can be obtained, regarding the total O&M costs (e.g., the usability of vessels or the average number of technicians).

2. O&M Offshore Wind Farms in the United States

The core of O&M activities lie in the equipment with which the technicians access the wind farm and repair the turbines. This equipment can be anything from CTVs to cranes to access systems. This section discusses the different logistic systems and select O&M equipment specific to this report.

2.1 O&M Equipment Requirement

This subsection describes different logistic systems based on their purpose. In this report, vessels are divided into two categories: access vessels and replacement vessels.

2.1.1 Access Vessels

Currently, in the European market, access vessels are categorized in several ways. In the last ECN O&M Report [11], the following classification was adopted: the types of CTVs according to their hull shape include :

- Monohull (the first CTV that was used),
- Catamaran (a mostly aluminium boat that is faster but also more expensive than a monohull),
- Trimaran (new to the market, this vessel consumes less fuel)
- Small waterplane area twin hull: (a catamaran-like vessel that achieves greater stability by minimizing the hull cross-section area at the sea's surface)
- Surface effect ship: (the technology of the SES has been adopted for CTVs; the hull shape of an SES CTV is similar to a catamaran, but most of the vessel's weight is listed by an air cushion, which provides high stability leading to high speeds, less fuel consumption).

In this study, only three types of primary access vessels were chosen: CTVs, SESs, and SOVs. The significant difference between a CTV (or SES) and SOV in this report is that a CTV needs to return to the harbor every day. Therefore, it is not possible for the technicians to stay offshore overnight. In this report, the CTV is categorized into three types: basic CTV, advanced CTV, and SES. This section describes the different characteristics and capabilities of the access vessels.

Basic CTV

A CTV is used to transfer technicians and small spare parts to the offshore wind farm when a maintenance operation has to be performed. A basic CTV (name used: CTV) is around 22 m long and can host 12 passengers and carry 5 tons. This maximum load can vary depending on the specific CTV model. Therefore, in this study, it is assumed that only small spare parts (< 5 tons) are allowed to be carried in this CTV. The average sailing velocity is 20 knots, with a maximum wind speed of 12 m/s and maximum wave height of 1.5 m for the highest-performing vessels.

Figure 3: Example of a basic CTV [12]



Basic CTVs are the most common vessels used to access offshore wind turbines. This kind of CTV is used for O&M purposes in offshore wind farms such as the Gunfleet Sands Offshore Windfarm [13].

Advanced CTV

An advanced CTV (name used: CTV+,) has the same function as the basic CTV, but with more sophisticated general characteristics. This vessel is around 26 m long and travels at 25 knots, making it larger and faster than the basic CTV. The advanced CTV can carry heavy loads (from 2 to 20 tons), operate at a higher wave height (2-m significant wave height), and transport 12 workers. Advanced CTVs are used in Round Three wind farms [14].

Figure 4: Example of an advanced CTV (CTV+) [15]

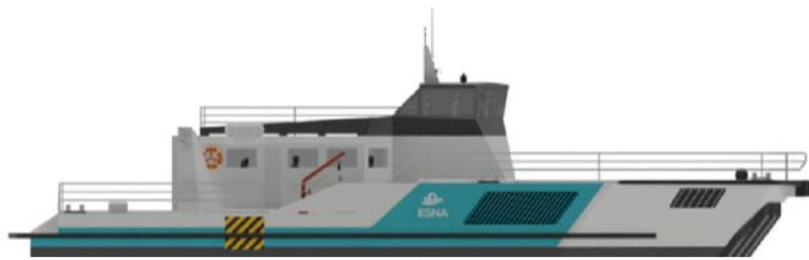


Surface Effect Ship

Even though the function of the vessel remains the same, an SES is different from the previously mentioned vessels regarding design. An SES is structurally similar to a catamaran but with the majority of its weight supported by an air cushion enclosed by the side hulls and a flexible seal

system at the bow and stern. This atypical design allows these vessels to operate at higher wave heights (2.5 m as a maximum) without losing the average sailing speed, which is approximately 35 knots [16]. They can transport 24–48 passengers, and in general, are larger than advanced CTVs. Because SESs have just arrived on the market, no wind farms are currently using them in their O&M strategy.

Figure 5: Example of an SES [17]



Service Operation Vessels

An SOV, also called a mother vessel, is part of the O&M strategies considered for far offshore wind farms. An SOV can host technicians, spare parts, and repair facilities offshore. Thus, O&M tasks are conducted more efficiently and longer transfer time is avoided. An SOV is much bigger than other vessels: more than 80 m long and able to carry 60 passengers and more than 2,000 tons. SOVs can operate at a significant wave height up to 3 m and a speed of 10–15 knots, which is slower than a CTV. The sailing speed of the SOV is not critical in this study as it stays offshore overnight.

It is assumed that an SOV stays in the wind farm and travels back to the shore every 2 weeks. Two “daughter crafts” support these boats as alternative access vessels for small repairs and inspections that require only technicians and hand tools. Because it is assumed that the daughter craft is included in the SOV contract, the price of this ship is null. In this study, the daughter crafts have the limitation of a 1-m wave height and 10-m/s wind speed for transfer and a 1.25-m wave height and 12-m/s wind speed for travel. Currently, an SOV is used in far offshore wind farms such as Gemini in the North Sea [18].

Figure 6: Example of an SOV [19]



Helicopter

In addition to the access vessel, a helicopter can be used to increase the weather window. For example, if a CTV is required and the weather accessibility is low, a helicopter might be a viable option. The advantages of using a helicopter are the short travel time and the least dependency on wave height.

Because a helicopter cannot carry large spare parts, it can only be used for inspections or small repairs. Currently, helicopters are used for turbine O&M purposes at the Horns Rev Project in Denmark, the Alpha Ventus Offshore Wind Farm in Germany, Global Tech 1 in the North Sea off Germany, and the Gemini Wind Farm off the coast of the Netherlands.

Figure 7: A helicopter transporting a technician to a wind turbine [20]



2.1.2 Vessels for Replacement

The vessels for replacements discussed in this report consist of a jack-up barge, which is used to carry large spare parts of 100 MT, a diving support vessel, and cable support vessels. A picture of a jack-up barge is shown in Figure 8. Today, cable vessels and jack-up barges that specialize in offshore wind farm operation are not available in the United States. Thus, it is assumed that the jack-up barge and the cable-laying vessel come from Europe. As a result, mobilization time and demobilization time are increased when compared with the value in the ECN O&M Calculator model for European region studies. In addition, the prices of rented vessels from Europe are also affected, and assumed to be more expensive.

As far as locations in the United States, Great Lakes, and Pacific Coast are concerned, the mobilization times and prices of these vessels coming from Europe have to be updated depending on the region. In the Great Lakes, only smaller boats can be used to access a wind farm, which lowers the costs of the ship. However, additional time is needed to access the lake (e.g., in this case, 1 week is considered as the time needed to access the Great Lakes from the Atlantic Ocean).

Figure 8: Example of a jack-up barge [21]



To satisfy the requirements of the Jones Act, a U.S.-flagged support barge is expected to be required and considered to be available as a support vessel for replacement activities. The main task of this U.S. barge is to carry the large spare parts from harbor to the wind turbines and come back with the replaced components. The additional cost is added for leasing these vessels.

For wind farms with floating wind turbines, a towing vessel similar to an anchor handling tug supply can be used to replace the jack-up barge. This vessel is assumed to be built in the United States. Figure 9 shows the installations of offshore wind turbines. However, these types of towing vessels can be applied for component replacements of the floating wind turbines. In this report, two support tug vessels are used to facilitate the towing operation.

Figure 9: Example of towing vessels



More details on O&M equipment can be found in Section 3 of the *Reference O&M Concepts for Near and Far Offshore Wind Farms* [22]. The vessel specifications are given in Section 4, which summarizes the logistic and cost specifications of a towing vessel considered for this report.

2.2 U.S. Vessel and Logistics Trends

As stated in the *2016 Offshore Wind Technologies Market Report* [10], offshore wind projects are expected to move to sites that are farther from shore, in deeper water, and subject to more severe meteorological ocean (metocean) conditions. Simultaneously, there is a trend toward larger turbine sizes, which are characterized by bigger, heavier components and higher hub heights. As a result of this growth in size and weight, new logistical challenges related to

construction and maintenance activities have surfaced. The U.S. industry has its own particular set of challenges, introduced by Jones Act requirements,¹ which are leading developers to modify installation strategies to match the capabilities of the existing U.S. vessel fleet. These strategies, which are generally perceived to be less efficient than those that can be achieved with the purpose-built fleet of vessels in Europe, could result in a cost premium for the initial U.S. projects. The U.S. offshore wind industry is currently investigating options to obtain a Jones-Act-compliant turbine installation vessel by retrofitting an existing vessel or constructing a new one. In July 2017, Zentech Inc. and Renewable Resources International announced their intention to deliver the first Jones-Act-compliant, four-legged, self-propelled, dynamically positioned level 2 jack-up vessel to the emerging U.S. offshore wind industry [23], [24], [25].

¹ The Jones Act (also known as the *Merchant Marine Act of 1920*) prohibits the transfer of merchandise between “points in the U.S.” unless the owner and crew of the vessel are “American,” as certified by the Secretary of Transportation. The Secretary may, however, choose to grant an exemption if no suitable American vessels exist [39].

3. Six Prospective Sites for U.S. Offshore Wind Farms

This analysis considers six prospective offshore wind sites placed within four distinct regions off the coasts of the United States. Two of the offshore sites are placed in the Atlantic, one in the Gulf of Mexico, one in the Great Lakes, and two in the Pacific (Figure 1). Each site has a unique geographic location and therefore comprises different wind power plant characteristics (Table 2) and metocean conditions (i.e., wind speed and wave height). Correlated time series metocean data sets are obtained from buoy data at the National Data Buoy Center (NDBC) [26] and data provided from the Wave Information Studies (WIS) [27] nearby each of the sites. The wind speed measurements for the sites are recorded at 5 m above the sea surface for NDBC wind speed data and 10 m above the sea surface for wind speed data from the WIS. For calculating wind farm downtime as a result of poor weather conditions, these wind speeds were extrapolated to the site's assumed turbine hub height using the power law with a 0.1 shear exponent. Although the duration of the time series data set differs for each of the sites, analysts strived to achieve at least 7 years of historical metocean data.

The ports assumed for the wind power plant's operations, scheduled maintenance, and unscheduled maintenance are selected using the World Port Index [28]. The World Port Index contains the location, physical characteristics, facilities, and services offered by major ports and terminals worldwide. Physical characteristics, such as port water depth and overhead clearance restrictions, are considered for selecting the ports for the six offshore wind sites. Four of the sites assume the same O&M port for both everyday operations and scheduled maintenance of the wind power plant and unscheduled maintenance; however, two of the sites require a different port that will accommodate the deeper draft requirements and overhead clearance requirements of a heavy-lift boat. The distances from the ports to the project sites are estimated using routes determined by satellite images. The six sites are described in more detail in this section of the report.

Figure 10: Locations of six prospective U.S. offshore wind farm sites

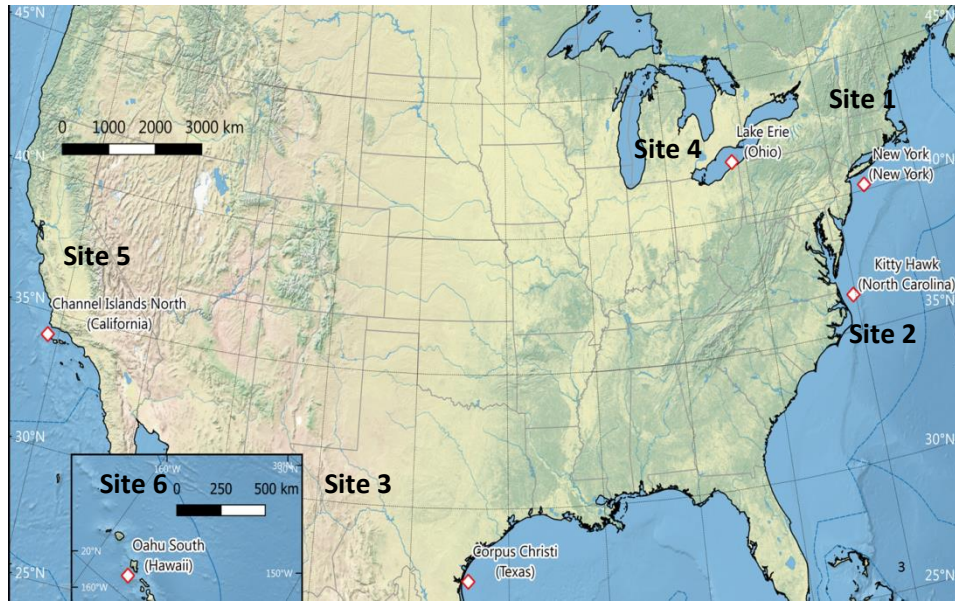


Table 2: Characteristics of Six Sites

Parameters	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Wind Plant Capacity (MW)	600	600	600	345	600	400
No. of Turbines	100	100	100	100	75	50
Turbine Size (MW)	6	6	6	3.45	8	8
O&M Port Distance (km)	70	143	102	22	127	30
Water Depth at Wind Site (m)	30	30	25	22	575	700

3.1 Site 1: North Atlantic, New York Wind Energy Area

Site 1 Location and Wind Farm Characteristics

The prospective offshore site in the North Atlantic region is placed near the approximate center of the New York wind energy area. This site is generically named Site 1 for the purposes of this study. This prospective site considers a 600-MW wind power plant comprising 100 turbines rated at 6 MW. The site is about 70 km to the nearest operations port around the Sandy Hook Bay and about 75 km to the nearest large port that is capable of accommodating a heavy-lift boat near the St. George Terminal. Because of the high congestion of marine traffic in this region of the United States, the mobilization time for heavy-lift boats to conduct an unscheduled maintenance activity was adjusted. The average 30-m water depth for this site lends it to using a fixed-bottom substructure technology, such as a monopile or jacket. For this analysis, we assume a jacket substructure supports the turbines for all fixed-bottom sites. A map with the marked geographic location of the New York site is shown in Appendix A. The energy production is estimated using the generic 6-MW wind turbine power curve [29] (shown in Appendix B).

Site 1 Met ocean Condition

The time series weather data for Site 1 was obtained from Buoy Station 44025 of the NDBC, located about 6 km from the approximate center of the wind farm. This data set contains 14 years of hourly time series wind and wave data from 1992 to 2005. As with most time series data sets,

there tends to be gaps in the data set; therefore; analysts omitted certain years that did not have a complete set of data. The resulting annual average wind speed for Site 1 is 8.97 m/s at a 100-m hub height with an average significant wave height of 1.27 m.

Table 3 shows a summary of the metocean conditions for Site 1. Weather patterns for this region of the United States may see higher wind speeds in the summer and autumn months, with a recorded maximum average wind speed of 30.45 m/s. These higher seasonal wind speeds may be influenced by tropical storms that are often observed at the end of summer and beginning of autumn. A graphical representation of the weather windows is presented in Appendix C.

Table 3: Weather Characteristics for the New York Site

	Annual			
	Average	Minimum ²	Maximum ³	Standard Deviation
Wind Speed (at 100 meter hub height); (m/s)	8.97	0	30.45	4.58
Significant Wave Height (m)	1.27	0	9.65	0.73

3.2 Site 2: North Carolina, Mid-Atlantic, Kitty Hawk Wind Energy Area

Site 2 Location and Wind Farm Characteristics

This 600-MW prospective wind power plant located near the approximate center of the Kitty Hawk wind energy area (about 143 km from the port infrastructure near Newport News). The wind farm utilizes 100 turbines rated at 6 MW that are placed on a jacket substructure in 30-m water depths. A map with the marked geographic location of the Kitty Hawk site is shown in Appendix A. The energy production is estimated using the generic 6-MW wind turbine power curve.

Site 2 Met ocean Condition

The time series wind and wave data for this site are obtained from the WIS (Station ID 63211). This data set contains 34 years of hourly time series wind and wave data from 1980 to 2014. The time series wind speed data revealed the presence of tropical storms, with a recorded maximum average wind speed of 46.5 m/s. The site's annual average wind speed is 8.31 m/s at a 100-m hub height and an average significant wave height of 1.35 m. Table 4 summarizes the wind and wave data for this site. A graphical representation of the weather windows is presented in Appendix C.

Table 4: Weather Characteristics for the Kitty Hawk Site

	Annual			
	Average	Minimum ²	Maximum ³	Standard Deviation
Wind Speed (at a 100-m hub height); (m/s)	8.31	0.13	46.5	4.03
Significant Wave Height (m)	1.35	0	10.53	0.75

² Minimum value in given year of datasets

³ Maximum value in given year of datasets

3.3 Site 3: Texas, Gulf of Mexico, Corpus Christi

Site 3 Location and Wind Farm Characteristics

The prospective wind power plant for Site 3 comprises 100 turbines each rated at 6 MW on jacket substructures in water depths averaging 25 m. The wind farm is about 102 km from the O&M port located in Corpus Christi Bay.

A map with the marked geographic location of the Corpus Christi site is shown in Appendix A. The energy production is estimated using the generic 6-MW wind turbine power curve [29] (shown in Appendix B).

Site 3 Met ocean Condition

The Gulf of Mexico has the potential for tropical storms and hurricanes. For Site 3, analysts use 22 years of time series wind and wave data from WIS Buoy 73034, for the years 1990 to 2012. During these years, we observed two hurricanes (i.e., Hurricane Bret and Hurricane Dolly) that passed near Site 3. During Hurricane Bret in late August of 1999, the maximum sustainable wind speed recorded was 61.7 m/s (from the time series data set). The annual average wind speed at 100 m is 8.88 m/s, with an average significant wave height of 1.08 m. Because this region of the United States has the potential to experience hurricanes, additional analysis is considered to better understand the impacts of hurricanes on wind power plant O&M costs. Additional detail on this hurricane case study is presented in Section 6.2., and a summary of the metocean statistics using the WIS time series data is shown in Table 5.

Table 5: Weather Characteristics for the Corpus Christi Site

	Annual			
	Average	Minimum ²	Maximum ³	Standard Deviation
Wind Speed (at a 100-m hub height); (m/s)	8.88	1.88	32.5	3.31
Significant Wave Height (m)	1.08	0.05	6.98	0.56

3.4 Site 4: Ohio, Great Lakes, Lake Erie

Site 4 Location and Wind Farm Characteristics

Site 4 is located in Lake Erie. For this site, analysts selected a 3.45-MW turbine because of limitations introduced by the Saint Lawrence Seaway. The series of locks in the seaway limit the size of the turbine installation vessel that can navigate from the Atlantic Ocean to the Great Lakes. Site 4 assumes the installation of 100 turbines placed on fixed-bottom monobucket substructures in 22 m of water depth. The monobucket substructure is utilized to endure the icing effects typical of freshwater in the Great Lakes. The Port of Ashtabula is assumed for the operations and scheduled maintenance activities approximately 22 km from the wind power plant. This port is assumed as not being capable of hosting a large lift boat for sizeable unscheduled maintenance repairs; therefore, Presque Isle Bay, about 75 km from the wind site, is used when a large lift boat is required.

A map with the marked geographic location of the Lake Erie site is shown in Appendix A. The energy production is estimated using the generic 3.45-MW wind turbine power curve (shown in Appendix B).

Site 4 Metocean Conditions

One particular challenge for this site is the development of ice during the winter months. The icing data is obtained from the National Oceanic and Atmospheric Administration's Great Lakes Ice Atlas [30], which reports the time series ice coverage in terms of a percentage. These data are correlated with the time series wind and wave data obtained from WIS Station ID 92053 that contains 14 years of continuous data from 1982 to 2002. From the Ice Atlas data set, it is estimated that ice is present about 11 weeks per year in Lake Erie.

A summary of the metocean statistics using the WIS time series data is shown in Table 6.

Table 6: Weather Characteristics for the Lake Erie Site

	Annual			
	Average	Minimum ²	Maximum ³	Standard Deviation
Wind Speed (at 87 meter hub height); (m/s)	7.00	0.21	26.20	4.09
Significant Wave Height (m)	0.52	0.00	4.68	0.58

3.5 Site 5: California, Pacific, Channel Islands North

Site 5 Location and Wind Farm Characteristics

The prospective Site 5 near the Channel Islands off the Coast of California comprises 75 turbines rated at 8 MW each. The water depths at this site are on average 575 m deep; hence, a floating offshore substructure (e.g., semisubmersible substructure) is required to support the turbine. The port infrastructure nearest the north end of the Channel Islands is Port Hueneme approximately 127 km from the wind farm. The operations, scheduled maintenance, and large unscheduled maintenance activities are assumed to be conducted from this port.

A map with the marked geographic location of the Channel Islands site is shown in Appendix A. The energy production is estimated using the generic 8-MW wind turbine power curve [29] (shown in Appendix B).

Site 5 Met ocean Condition

The time series wind and wave data for this site are obtained from NDBC Station 46054. The correlated time series data contain 16 years of data from 1994 to 2010. Years with missing data were omitted from the time series data set used as inputs into the model. In general, the Pacific Ocean tends to have harsher sea states than the Atlantic, with an average annual wind speed of 10.5 m/s at a 112-m hub height and average annual significant wave height of 2.01 m. A summary of the metocean statistics using the NDBC time series data is shown in Table 7.

Table 7: Weather Characteristics for the Channel Islands Site

	Annual			
	Average	Minimum ²	Maximum ³	Standard Deviation
Wind Speed (at a 112-m hub height); (m/s)	10.51	0.00	45.72	5.37
Significant Wave Height (m)	2.01	0.00	8.84	0.82

3.6 Site 6: Hawaii, Oahu South

Site 6 Location and Wind Farm Characteristics

The prospective Site 6 off the coast of Oahu consists of 50 turbines rated at 8 MW. Because the site's water depth is about 700 m, the turbines are supported by semisubmersible floating substructures. The operations, scheduled maintenance, and large unscheduled maintenance repairs are carried out near the Honolulu Harbor about 30 km from the wind site.

A map with the marked geographic location of the Oahu South site is shown in Appendix A. The energy production is estimated using the generic 8-MW wind turbine power curve [29] (shown in Appendix B).

Site 6 Met ocean Condition

The WIS Station ID 82551 buoy is used to obtain the time series metocean data near the South Oahu site. The wind and wave data are correlated with 31 years of historical data measured hourly from 1980 to 2011. The average annual wind speed at a 112-m hub height is 8.38 m/s, with an annual average significant wave height of 1.34 m. A summary of the metocean statistics using the WIS time series data is shown in Table 8.

Table 8: Weather Characteristics for the Hawaii Site

	Annual			
	Average	Minimum ²	Maximum ³	Standard Deviation
Wind Speed (at a 112-m hub height); (m/s)	8.3	0.38	28.9	2.81
Significant Wave Height (m)	1.34	0.49	7.98	0.43

4. Modelling Approach

Multiple O&M models were created for each of the six wind farm sites using the ECN O&M Calculator. For every site, suitable modeling inputs (Section 4.1) were considered and inserted. Most of the inputs were based on reliable and sourced information from the National Renewable Energy Laboratory (NREL). However, in some cases, appropriate assumptions were made based on experience and knowledge of NREL and ECN experts. The inputs included weather conditions at each site, wind turbine failure characteristics, a resource overview for performing O&M, a maintenance strategy for performing repair activities, etc. Thereafter, simulations (Section 4.2) were run for each of the O&M strategies and the most suitable or cost-effective strategy was selected (Section 4.3).

4.1 Inputs

To model O&M scenarios in the ECN O&M Calculator, various inputs are required. They are discussed in the following subsections.

4.1.1 Wind Farm Characteristics

General Wind Farm Configuration

The six wind farm sites (discussed in Section 3) were chosen with different configurations. The following compositions represent the wind farm for each site:

- Site 1, 2, and 3 (New York, Kitty Hawk, Corpus Christi): one hundred 6-MW turbines with monopile substructures
- Site 4 (Lake Erie): one hundred 3.45-MW turbines with monobuckets (icebreaker)
- Site 5 (Channel Island North): seventy-five 8-MW turbines with semisubmersible substructures
- Site 6 (Oahu South): fifty 8-MW turbines with semisubmersible substructures.

Weather Data

NREL provided weather data for each site considered for the study. The weather time series data consist of average wind speeds of 5 or 10 m and a significant wave height for a duration of at least

5 years. For Site 2, Site 3, Site 4, and Site 6, the weather data were obtained from WIS Stations ID 63211, 73034, 92053, and 82551 at 10 m above the sea level. On the other hand, for Site 1 and Site 5, the weather data were obtained at 5 m above the sea level from NDBC at Station ID 44025 and Station ID 46054. To extrapolate the wind speeds at 10 m above sea level, the wind speed is assumed to follow a power law with a shear exponent α of 0.1:

Equation 1

$$V_{HubHeight} = V_{recorded} \left(\frac{H_{HubHeight}}{H_{recorded}} \right)^\alpha$$

For some of the weather data that contain missing (Non A Number or NAN) values, data pretreatments were needed. The missing values were replaced by values from linear interpolation. When the number of NAN values for a particular year was too high, then the complete year was removed from the time series.

For Site 4, the presence of ice was quantified by the percentage of the lake covered by ice during winter. To take ice into account as a limiting accessibility parameter, the influence was reflected correspondingly on the wave height. For a particular time stamp, if the percentage of the ice was higher than the threshold allowed to access the wind farm, the wave height for that time stamp was set to 99 m, signifying inaccessibility to the wind farm.

Electricity Prices

The forecasts of electricity prices are different across the states in the United States. This parameter significantly influences the O&M cost, specifically the revenue loss during downtime. To make the simulation as realistic as possible, the levelized avoided cost of energy (LACE) was used to calculate the “foregone revenue/opportunity cost.” LACE is a combination of prevailing 2014 electricity prices (annual average) and the capacity value [31]. As capacity value from offshore wind is relatively small, LACE mostly represents prevailing electricity prices. Because no information on LACE was found for Hawaii, the ‘residential rate’ of 27.4 cents\$/kWh for Oahu was used. The values forecasted by NREL are summarized in [31]. Moreover, for the scope of this study, Table 9 details the assumed electricity prices for each wind farm site.

A sensitivity study on the electricity prices was conducted to evaluate the influence of these prices on the O&M KPIs. Because LACE is constant throughout the wind farm lifetime and lower than the LCOE, the revenue losses and total O&M costs reported might be underestimated.

Table 9: Baseline Electricity Prices Considered for the Six Wind Farm Sites

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Region	North Atlantic	Mid-Atlantic	Gulf of Mexico	Great Lakes	Pacific	Hawaii
Name	New York Lease Area	Kitty Hawk	Corpus Christi	Lake Erie	Channel Islands North	Oahu South
LACE (2015\$/kWh)	0.071	0.042	0.044	0.052	0.050	0.274 ⁴

⁴ For Site 6 – Hawaii, residential rate of electricity is considered in contrast to LACE prices assumed for the other five sites.

4.1.2 Maintenance Definitions

Corrective-Based Maintenance

Corrective-based maintenance is performed when a component fails. Thus, the failure rates of every component have to be defined. The failure rates of each wind turbine component were derived from the results of the Reliawind project [32]. The failure rates used in this study are listed in Table 10 and Table 11.

Table 10: Baseline Wind Turbine System Component Failure Rate Assumption

Wind Turbine System Components (Based on RDS-PP Taxonomy)	Annual Failure Frequency of Main Turbine Components (failures/wind turbine/year)
AB Lightning protection/grounding	0.012
MD Wind turbine	5.407
MDA10 Rotor System - blades	0.067
MDA20 Rotor system - hub	0.067
MDC Blade adjustment	0.815
MDK10 Drivetrain - main shaft/bearing	0.013
MDK30 Drivetrain - brake system	0.022
MDL Yaw gearbox	0.287
MDX Hydraulic system	0.057
MDY Control and protection system turbine	0.903
MKA Generator	0.438
MKY Control and protection system generator	0.796
MSA Generator lead/transmission cables	0.487
MST Transformer	0.082
MUD Machinery enclosure	0.014
UMD Turbine structure/tower	0.159
XA Heating, ventilation, air conditioning	0.015
XM Crane system	0.016

Table 11: Baseline Balance-of-Plant Component Failure Rate Assumption

Balance-of-Plant Components	Annual Failure Frequency of Main Turbine Components (failures/wind turbine/year)
Transformer 1	0.554
Transformer 2	0.554
Foundation/Scour Protection	3.369
Cables	0.053

Calendar-Based Maintenance

The calendar-based maintenance is scheduled or planned in summer to make the best use of the available weather window during less extreme weather conditions. In this study, the calendar-based maintenance was scheduled every year from the 1st of May to the 30th of July.

Condition-Based Maintenance

Additionally, condition-based maintenance is performed every 5 years for planned large component replacements. These maintenance activities are conducted during a 6-month period between the 1st of April to the 30th of September. In this study, further sensitivity analysis was performed to see the influence of this type of maintenance in hurricanes cases (Section 6.2).

Repair Classes

Repair classes were classified based on the duration of the maintenance, the types of maintenance (inspection, repair, or replacement), and the spare parts used in the replacement operation. Table 12 summarizes the repair classes used in this study. The details of these maintenance operations are given in Appendix E.

Table 12: Repair Classes Used for the Baseline

Type of Maintenance	Name
Unplanned Corrective	Remote reset
	4h Inspection/small repair inside
	8h Inspection/small repair outside
	8h Replacement parts (< 2MT)
	16h Replacement parts (< 2MT)
	24h Replacement parts (< 2 MT)
	24h Replacement parts (< 100 MT)
	40h Replacement parts (< 100 MT)
	8h Balance-of-Plant transformer repair
	48h Balance-of-Plant transformer repair
	8h Balance-of-Plant Foundation/scour protection
	32h Balance-of-Plant cable replacement
Condition Based	48h Wind Turbine preventive maintenance
Calendar Based	24h Wind Turbine preventive maintenance

Optimization of Length of Calendar and Condition Based Maintenance

As mentioned, planned maintenance including calendar- and condition-based maintenance are usually performed during the summer period. But, finding the right weather window and length of the window is important. This is especially critical when employing slower and lower capability vessels, because the maintenance operations need more time. Moreover, the duration of the maintenance period increases when the vessel speed decreases and the waiting time due to weather increases. Some sets of simulation were conducted for Site 1 only to determine the optimum length of maintenance periods. However, this same method can be applied to other sites as well. Table 13 shows the recommended length of maintenance period for Site 1.

Table 13: Recommended Length of Planned Maintenance for Site 1

	Length of the Calendar-Based Maintenance Required	Length of the Condition-Based Maintenance Required
CTV	5 months	12 months
CTV+	4 months	9 months
SES	4 months	7 months
SOV	3 months	6 months

4.1.3 Resources Overview

Access Vessels

As a first step, the optimum number of access vessels was identified. The objective was to find the minimum number of the access vessels with which all maintenance tasks could be finished. Based on that, the strategies with an optimized number of access vessels were compared.

As mention in Section 2.1.1, fixed yearly prices were used for all access vessels except helicopters. The helicopter is considered as a secondary access vessel that is contracted on an as-needed basis; hence, the daily rate was used. In addition, appropriate fuel charges were added per trip. The fuel

price used for the fuel surcharge calculation is 4.5\$/L. The travel time was computed for each site depending on the vessel speed and the distance from the nearest O&M harbor. Access vessels do not require mobilization or demobilization cost and time as they are leased on a yearly or longer-term basis. For the helicopter being leased on a daily basis, a mobilization time of 8 hours and a demobilization time of 4 hours was needed and the corresponding cost of this operation was 6,300\$/mob.

Specifically for Site 4, all access vessels except the helicopter were assumed to be able to access the wind farm when the ice coverage is below 10%⁵. An icebreaker was introduced for this site as an alternative access vessel. It has the same limitations, wave height, wind speed, number of technicians, and travel time as a CTV. However, the icebreaker has a higher daily price (6,140\$/day). The advantage of this access vessel is its ability to access a wind farm during icing conditions. The icebreaker assumed in this study can access the wind farm under 50%⁵ of ice coverage.

Table 14 summarizes the prices of all access vessels presented in Section 2.1.1.

Table 14: ECN O&M Calculator Inputs for the Access Vessels

	Unit	Crew Transfer Vessel	Crew Transfer Vessel +	Surface Effective Ship	Service Operating Vessel	Helicopter
Optimized Number of Vessels		2	2	1	1	-
Vessel Speed	knot	20	25	35	15	Default
Fuel Consumption Rate	gal/h	25	25	20	25	55
Technicians Capacity		12	12	48	60	6
Maximum Wave Height Travel	m	1.5	2	2.5	3	4
Maximum Wind Speed Travel	m/s	12	15	17	20	20
Maximum Wave Height Working	m	1.5	2	2.5	4	4
Maximum Wind Speed Working	m/s	12	15	17	12	20
Fixed Yearly	k\$/year	840	1 950	2 700	15000	0
Daily (Working & Waiting)	\$/day	-	-	-	-	6300

Vessels for Replacement

For the vessels for replacement, the travel time is included in the mobilization and demobilization time (there is no fuel surcharge), except for the U.S.-flagged support barge, in which the travel time is computed depending on the distance of the nearest O&M harbor. The price considered is the daily rate price, and the price used for the waiting rate is 75% of the working price. The prices for these vessels are derived from an NREL report on hurricanes studies [33]. Table 15 shows the ECN O&M Calculator inputs of these prices.

⁵ Accessibility of CTVs and ice breakers are assumed based on engineering estimation

Table 15: ECN O&M Calculator Inputs for the Replacement Vessels

	Unit	Jack-Up Barge	Diving Support Vessel	Cable Laying Vessel	U.S. Flagged Support Barge
Mobilization Time	h	720	360	720	360
Demobilization Time	h	48	0	0	0
Maximum Wave Height Travel	m	5	5	5	5
Maximum Wind Speed Travel	m/s	25	25	25	25
Maximum Wave Height (Working)	m	2	2	2	2
Maximum Wind Speed (Working)	m/s	10	25	10	12
Daily Rate (Working)	k\$/day	140-105 ⁶	98	19.5	70
Daily Rate (Waiting)	k\$/day	105-78.75 ⁶	73.5	14.625	52.5
Mobilization/Demobilization	k\$/mob	1,000–1,250 ⁶	975	5050	• 1000

For wind farms on the West Coast (Pacific) with floating wind turbines, the jack-up barge is replaced by a towing vessel and two small support tugs. The characteristics of these vessels are presented in Table 16. The travel time and fuel surcharge for these two vessels were calculated based on the offshore tug (120BP) speed during the towing operation. The travel time when the boat is not towing and the fuel surcharge associated were added to the mobilization time and price. The mobilization and demobilization prices were computed by multiplying the mobilization or demobilization time with the daily rate.

Table 16: ECN O&M Calculator Inputs for the Towing Vessels and Support Tugs

	Unit	Offshore Tug (120 BP) + Survey Equipment	Small Support Tug
Vessel Speed	knot	3.2 (average speed when towing)	8.6 (limited to offshore tug speed when supporting tow)
Mobilization Time	h	48	48
Demobilization Time	h	48	48
Capacity - Technicians		20	13
Maximum Wave Height (Travel)	m	4.5 (transit and towing)	4.5 (transit and towing)
Maximum Wind Speed (Travel)	m/s	20 (transit and towing)	20 (transit and towing)
Maximum Wave Height (Working)	m	2.5 (disconnect power cables, mooring lines, etc.)	2.5 (disconnect power cables, mooring lines, etc.)
Maximum Wind Speed (Working)	m/s	16 (disconnect power cables, mooring lines, etc.)	16 (disconnect power cables, mooring lines, etc.)
Work	\$/day	40000	10000
Wait	\$/day	40000	10000

Technicians

To ensure the realization of maintenance schedules, technicians and vessels have to be available and able to access the wind farm when required. In this study, the salary of technicians is assumed to be 125\$/h. The vessels determine the maximum number of technicians that can be carried. However, for consistency, the number of technicians available for every strategy was kept the same (i.e., 24). For all strategies considered, except the SOV, the shift pattern is defined as having

⁶ Prices used in the Great Lakes region

one shift of 12 hours starting at 7 a.m. throughout the year. For the SOV strategy, two shifts were defined from 7 a.m. to 7 p.m., with 16 technicians, and from 7 p.m. to 7 a.m., with six technicians.

Spare Parts

To estimate the repair costs accurately, the spare parts prices and logistics time have to be defined. The logistics time or the lead time and the associated costs are added to the total repair time and costs when performing maintenance. It is noted that there is no logistics delay time associated with condition- and calendar-based maintenance. Table 17 shows the spare parts specifications used in this study.

Table 17: Spare Parts Logistic and Prices Definition

Maintenance	Name	Logistic Time	Material Costs		
		h	\$		
			6 MW fixed	3.45MW	8 MW floating
Unplanned Corrective	Consumables 0.5k	0	500	250	750
	Small Parts 5k in Stock (< 2 MT)	0	5,000	2,500	7,500
	Small Parts 50k 48h (<2 MT)	0	50,000	25,000	75,000
	Small Parts 250k 48h (<2 MT)	0	250,000	125,000	375,000
	Large Parts 100k 168h (<100 MT)	168	100,000	50,000	150,000
	Large Parts 100k 336h (<100 MT)	336.00	100,000	50,000	150,000
	Large Parts 500k 336h (<100 MT)	336	500,000	250,000	750,000
	Transformer 250k 1440h (<25 MT)	1440	250,000	125,000	375,000
	Small Parts Found./Scour 5k 48h	48	5,000	2,500	7,500
	Cable 350k 240h	240	350,000	175,000	525,000
	No Costs	0	0	0	0
Condition Based	Small Parts 30k	-	30,000	15,000	45,000
Calendar Based	Small Parts 10k	-	10,000	5,000	15,000

4.2 Simulations

Initially, to limit the number of cases, unrealistic strategies were sorted out (e.g., a strategy with travel time longer than 4 hours or wherein the site weather restrictions were too harsh for a strategy to be implemented). Thereafter, the strategies that resulted in at least 95% of time and yield availability were shortlisted. Lastly, out of the remaining suitable strategies for each case, the trade-off was made between the highest availability and lowest cost of repair, thereby leading to the most cost-effective O&M strategy.

Further, simulation lengths of 1, 5, and 20 years were tested to determine the duration of simulation needed to get convergence results on availability. Five years were considered to be sufficient to get the convergence results, whereas with 20 years, the computation time increased

drastically. Hence, for all simulations, 5 years were chosen, with the first year as the n starter period.

The convergence criteria was set at 0.05% downtime for at least 25 consecutive simulations. The differences in total O&M costs and costs per kWh were observed to be lower than 5% between 5- and 20-year simulations. Consequently, the cost deviation lower than 5% was considered to be not significant.

4.3 Outputs

For every shortlisted case, various KPIs were obtained. The main KPIs included time-based availability (%), yield-based availability (%), repair cost (k\$), cost of Revenue loss (k\$), and total O&M costs (k\$). Furthermore, the utilization of technicians and equipment for all cases were also evaluated to optimize the results.

5. Baseline Results

As explained in 4.1.3, five access vessels and their combinations were considered to evaluate the O&M strategies for each site. All of the results are based on the input parameters that were assumed to be representative for the U.S. prospective offshore wind farms. Based on considerations of distance and weather condition, some of the cases are excluded. Table 18 provides the simulation plan.

Table 18: Strategy Optimization Simulation Plan⁷

Site	CTV	CTV+	SES	SOV	CTV & Helicopter	CTV+ & Helicopter	SOV & Helicopter
1							
2	Distance				Distance		
3					Distance		
4	Distance & Met ocean Conditions				Distance & Met ocean Conditions		
5							

5.1 Site 1: North Atlantic, New York Wind Energy Area

For Site 1, three strategies are able to achieve more than 95% availability in time. However, by comparing the OPEX (c\$/kWh) of these strategies, using an SES as the primary access vessel would provide the most cost-effective solution for the operator. The results of this site are shown in Table 19.

Moreover, an SOV can be considered as an alternative solution. Using an SOV would ensure higher accessibility, directly leading to higher availability. However, the high price of an SOV will become a trade-off with higher availability for the operator. In Section 5.2, a sensitivity study on SOV price is discussed in which the price of the SOV is competitive with the SES.

⁷ Brown block: these cases are excluded because of distance and weather limitations (as explained in Section 4.2).

Table 19: Site 1: North Atlantic – New York Lease Area O&M KPI Results Comparison

O&M Strategy	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M Costs (M\$/yr)
CTV	91.9	91.2	2.69	61.64	15.73	77.37
CTV+	94.2	93.8	2.34	55.07	11.2	66.27
SES	95.1	94.8	1.94	46.17	9.39	55.56
SOV	95.6	95.3	2.13	50.88	8.5	59.38
CTV & Heli	92.6	92.2	2.69	62.24	14.03	76.28
CTV+ & Heli	94.4	94.1	2.34	55.23	10.62	65.85
SOV & Heli	95.5	95.2	2.13	50.95	8.56	59.52

Furthermore, for all cases, it was observed that adding a helicopter as a support access vessel does not improve the availability and costs significantly. The main reason is that the helicopter is used only when the primary vessel is not available for maintenance or as alternative equipment, but never as a primary vessel. Moreover, a helicopter can only transport consumable parts and not spare parts (small or large). Therefore, it can only be used for inspection and minor repairs without spare parts. Lastly, as compared to an SOV that can be operated 24 hours a day, a helicopter can only operate under a single day shift. It was noted that the maximum usage of a helicopter occurs when using a CTV, and even then it constitutes only 15% of the total working time.

5.2 Site 2: North Carolina, Mid-Atlantic, Kitty Hawk Wind Energy Area

For a far-offshore wind farm, some of the primary access vessels were excluded in the comparison study because of the long travel time required for the technicians. Based on the results shown in Table 20, an SOV is the most suitable O&M strategy for Site 2. By using an SOV, the wind farm can operate at more than 95% availability, and at the lowest cost. An SES would not be suitable for this farm not only because it would provide lower availability and higher total O&M cost, but also because a two-way trip with an SES would take 4.5 hours. This high travel time is assumed to affect the technician's well-being. Therefore, operating the wind farm offshore is overall more beneficial for this case. A sensitivity study on the SOV price for this wind farm site is presented in Section 6.1.

Also, for Site 2, a helicopter coupled with an SOV does not improve the availability, because it is only used for 1% of the total working time. With a travel limit of a 3.0-m significant wave height and 20-m/s wind speed, an SOV is able to access a majority of the time when maintenance is needed. The results are shown in Table 20.

Table 20: Site 2: Mid-Atlantic – Kitty Hawk O&M KPI Results Comparison

O&M Strategy	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M Costs (M\$/yr)
SES	94.3	94.3	2.4	50.64	5.42	56.06
SOV	95.7	95.8	2.33	49.92	4.01	53.93
SOV & Heli	95.8	95.9	2.64	50.15	3.95	54.1

5.3 Site 3: Texas, Gulf of Mexico, Corpus Christi

Site 3 has a similar trend of results as observed in Site 1. However, contrary to Site 1, the CTV alone as an O&M strategy is not considered, as the two-way travel would take 5.5 hours. For this site, an SES is the most suitable strategy as it provides more than 95% availability and the lowest

OPEX. Similar to site 1, the SOV could also be an alternative solution if the operator is willing to pay a higher total O&M cost difference of 3M\$/year, which provides a marginal increase in availability of 0.6% . The model results for Site 3 are shown in Table 21.

Site 3 is chosen as the site that represents a higher chance of hurricanes. In Section 5.2, some hurricane-related sensitivity studies are explained, and the results are shown. This hurricane sensitivity study is also applicable for Site 1 and 2, which also have a high chance of hurricanes or tropical storms.

Table 21: Site 3: Gulf of Mexico – Corpus Christi O&M KPI Results Comparison

O&M Strategy	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M Costs (M\$/yr)
CTV+	94.4	94.3	2.01	49.77	6.5	56.26
SES	95.3	95.3	1.82	45.5	5.36	50.86
SOV	95.9	95.9	1.96	49.17	4.74	53.91
CTV+ & Heli	94.5	94.5	2.02	50.02	6.31	56.33
SOV & Heli	95.9	95.9	1.96	49.26	4.76	54.02

5.4 Site 4: Ohio, Great Lakes, Lake Erie

Particularly for Site 4, the presence of ice was introduced in the model as explained in Section 4.1.1. The results show how the ice can impact the O&M KPIs and how a different strategy can be applied during the period with ice. Two strategies were evaluated that are using the icebreaker instead of other access vessels and a helicopter as a secondary access vessel.

Ice Impact

To understand the impact of ice, two models were simulated using a CTV as the primary access vessel: one with no presence of ice and another with it. For the former case, the time-based availability of more than 95% is achieved. In the latter case, where in 11 weeks of ice is prevalent and considered, the availability drops down to around 90% (refer Table 22), thus resulting in a drop of 5% availability and an increase of 14% OPEX. Therefore, an alternative solution is needed for operating the wind farm so that even during the periods of ice, maintenance tasks can still be performed.

Icebreaker Strategy

One of the alternate strategies considered to access the wind farm during a period of ice is to use an icebreaker instead of a CTV. As explained in Section 4, an icebreaker can access the wind farm with ice coverage of up to 50%⁵. However, this improvement does not increase availability significantly (see Table 22). This is because there are fewer time stamps with ice coverage between 10% and 50% than the total number of time stamps. Approximately 14.6% of the weather data contain an ice level that is higher than 10% coverage and a 13.3% ice level that is greater than 50% coverage. The number of values between the 10% and 50% ice coverage represent only 1.3% of the entire weather data. Thus, availability improvement provided by the increase of ice limitation is negligible. Moreover, the icebreaker also has a higher capital investment cost that increases the total O&M costs by 10.4%. In conclusion, an icebreaker would not be recommended as an alternative strategy for this site.

Helicopter Strategy

For this case, the helicopter is assumed to be able to access the wind farms during the icing conditions under the wind speed limit of 20 m/s. By using a helicopter in addition to a CTV, the availability of the site can increase by 2.7%.

Table 22: Site 4: Great Lakes – Lake Erie O&M KPI Results Comparison

O&M Strategy	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M Costs (M\$/yr)
CTV without ice	95.2	95.2	3.75	36.75	2.59	39.34
CTV	90.6	89.4	4.28	39.39	5.74	45.13
CTV+	90.8	89.6	4.4	40.55	5.61	46.16
SES	90.3	89.2	4.38	40.18	5.83	46.02
SOV	90.4	89.3	5.1	46.83	5.79	52.63
Ice Breaker (IB)	90.4	89.2	4.85	44.51	5.85	50.37
CTV & Heli	93	92.5	4.27	40.62	4.04	44.67
CTV+ & Heli	93.3	92.9	4.37	41.76	3.85	45.62
SES & Heli	93.2	95.8	4.34	41.48	3.9	45.38
SOV & Heli	93.4	93	5.02	48.02	3.8	51.82
IB & Heli	92.9	92.3	4.8	45.64	4.15	49.79

As shown in Table 22, a helicopter improves the availability in all cases. The high cost of leasing a helicopter is offset by lower revenue losses achieved with higher accessibility during the icing period. Considering other cases, the combination of an SOV and a helicopter provides the highest availability of the wind farms. However, it gives a 15% higher electricity cost compared to the CTV case. Therefore, using a SOV would be too expensive for this case. Considering the cost and the availability, it can be concluded that using two CTVs with a helicopter (especially during the weeks of ice) is the most suitable strategy for this site. However, using a helicopter during ice periods can raise some safety issues. A further study to assess the safety of helicopter operation during an ice period needs to be conducted.

5.5 Site 5: California, Pacific, Channel Islands North

Because of the severe weather conditions (average of 2.01-m significant wave height) and long distance (127 km) at this site, only two primary access vessels are considered as options for O&M strategies. An SOV is the most suitable access vessel to be implemented. Similar to Sites 1-3, the helicopter does not improve the availability and the cost. The results are shown in Table 23.

Table 23: Site 5: Pacific – Channel Islands North O&M KPI Results Comparison

O&M Strategy	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M Costs (M\$/yr)
SES	93.1	93	1.19	33.96	10.88	44.84
SOV	95.2	95	1.31	38.18	7.75	45.94
SOV & Heli	95.2	95	1.32	38.48	7.66	46.14

5.6 Site 6: Hawaii, Oahu South

For this site, all the strategies except the CTV strategy could reach the target of 95% availability. Specifically, using two CTV+ gives the lowest cost per kWh and is the most suitable strategy to be implemented. Similar to Site 1 and 3 and regarding the high availability provided, an SOV may be an alternative strategy for this site to increase the availability. However, the owners need to pay 10% more for the total O&M costs per year. On the other hand, an SES is a better alternative

solution than the SOV as it costs lower while still reaching the targeted availability. The results of Site 6 are shown in Table 24.

Table 24: Site 6: Hawaii – Oahu South O&M KPI Results Comparison

O&M Strategy	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M Costs (M\$/yr)
CTV	94.1	93.6	1.35	21.12	29.36	50.48
CTV+	95.8	95.7	1.35	21.6	19.89	41.49
SES	96	96	1.36	21.7	18.55	40.25
SOV	96.3	96.3	1.81	29.1	17.18	46.28
CTV & Heli	94.8	94.6	1.37	21.63	24.95	46.58
CTV+ & Heli	95.8	95.7	1.36	21.67	19.61	41.29
SOV & Heli	96.3	96.2	1.82	29.18	17.42	46.6

6. Sensitivity Studies

In addition to the baseline scenarios, sensitivity studies were performed on parameters that were considered to vary depending on market situation and other assumptions. The main objective of these sensitivity studies was to better understand the challenges that are particularly relevant to the U.S. offshore wind market and industry. The following four sensitivity studies were performed:

- **Leasing price of primary access vessels**
Market maturity and varying availability of vessels between the U.S. and Europe are drivers for this analysis. The SOV and SES leasing prices were varied as part of this sensitivity and the results were evaluated and compared.
- **Extreme weather challenges**
The effect of occasional hurricanes in the Atlantic Ocean were detailed with alternative logistics and planning schedules. The influence on O&M KPIs was also observed.
- **Availability of vessels for replacement**
The option of U.S.-built vessels (especially large replacement vessels) and benefit of developing a U.S. based supply chain was evaluated. As mentioned before, as part of the simulation process, the baseline case assumed that the replacement vessels would arrive from Europe whenever large replacements were required. The effect of this sensitivity is quantified in terms of O&M KPIs.
- **Different parameter for electricity price**
Another parameter that influences the cost of revenue losses of the wind farm is the electricity prices. As discussed, constant LACE prices over time were used for the reasons explained before. However, because the values of the electricity price were relatively low, the impact of using LCOE prices was also evaluated for each wind farm scenario.

The above-mentioned sensitivity scenarios are discussed in detail in the following subsections.

6.1 Leasing Price of Primary Access Vessels

The SOV and SES both have greater capabilities than the CTV and CTV+ to access wind farms because of their weather limitations (which can be seen in Table 14). Moreover, it is expected that in all cases, the SES and SOV would provide the highest availability. However, as a result of the higher price of an SOV assumed for baseline cases, the SES would be the preferred strategy.

Therefore, the sensitivity study was conducted to determine the threshold of the SOV price that is competitive with the SES.

6.1.1 Model Inputs Changes

In this study, several hiring rates of an SOV and SES were considered. The baseline price assumed for an SOV is 12M\$/year. However, in the European market, the price of an SOV is reported to be between 25 to 30k€/day (based on a long-term lease), which corresponds to approximately 8M\$/year. Hence, in this sensitivity study, the SOV price was varied using a range of the following values: 18M\$/year, 15M\$/year, 12M\$/year, 7.5M\$/year, and 5M\$/year. The results for each case were evaluated and compared.

For the SES, two leasing prices were also assessed. In all baseline cases, the yearly hiring price of an SES is 4.5M\$/year. However, based on an NREL report [33], the hiring rate of an SES is 9k\$/day. As this study assumes the yearly hiring price is equal to the price of hiring an SES for 300 days (instead of 360 days), the annual price used for the comparison is 2.7M\$/year.

6.1.2 Results

As mentioned in Section 5, for Site 1 and 3, employing an SES as part of an O&M strategy provided the most cost-effective solution. Whereas, using an SOV provided the best availability. For Sites 1, 2, and 3, the sensitivity studies on SOV and SES leasing rates were conducted to evaluate the competitiveness of these vessels.

Site 1: North Atlantic, New York Wind Energy Area

For Site 1, the SOV yearly leasing price that results in the same total O&M costs as an SES (with yearly leasing prices of 4.5 M\$/year) is 7.5 M\$/year. Currently, there is no SOV at this price available. Moreover, if there is an SES with a cheaper yearly leasing price, in this case 2.7 M\$/year, the SOV price also needs to be cheaper, which is less than 6 M\$/year. Thus, for this site, an SES would be the most cost-efficient strategy as shown in Section 5.1. Figure 11 and Figure 12 shows the sensitivity results on the SOV and SES prices for Site 1.

Figure 11: SOV vs. SES fixed yearly prices sensitivity study for site 1

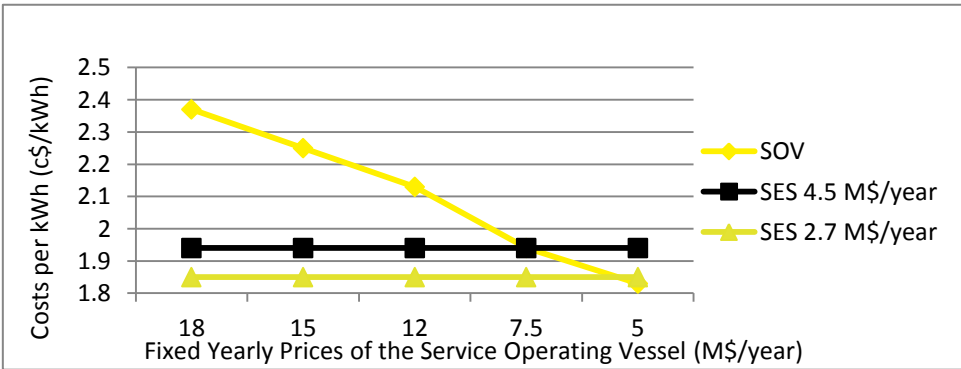
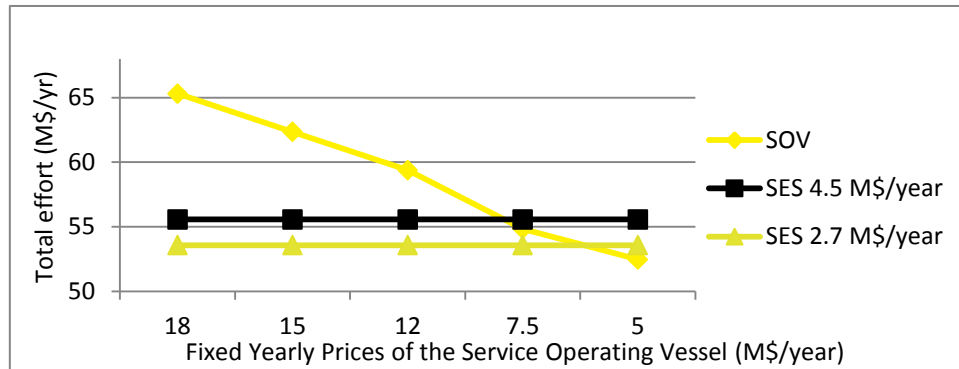


Figure 12: SOV vs. SES fixed yearly prices sensitivity study for site 1



Site 2: North Carolina, Mid-Atlantic, Kitty Hawk Wind Energy Area

For Site 1, the SOV yearly leasing price that results in the same total O&M costs with an SES (with yearly leasing prices of 4.5 M\$/year) is 13.5 M\$/year. This price is currently available on the market. Moreover, if there is an SES with a cheaper yearly leasing price, in this case 2.7 M\$/year, the SOV price also needs to be cheaper, which is less than 12 M\$/year. This price is also reported to be available in the market. Therefore, for Site 2, an SOV does not only provide the best availability but also gives the most cost-efficient strategy. Figure 13 and Figure 14 show the sensitivity results on the SOV and SES prices for Site 2.

Figure 13: SOV vs. SES fixed yearly prices sensitivity study for site 2 (Cost per kWh)

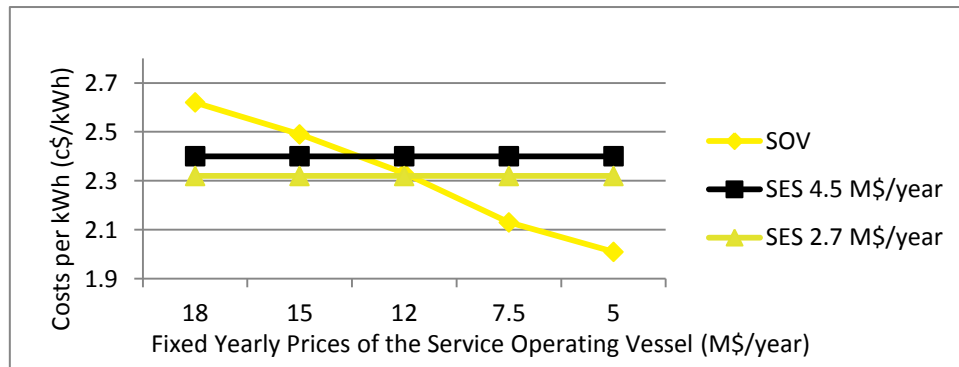
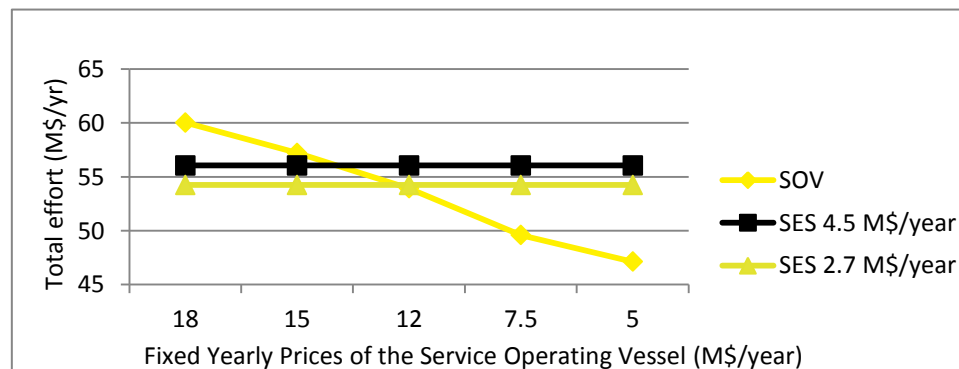


Figure 14: SOV vs. SES fixed yearly prices sensitivity study for site 2 (Total O&M Costs)



Site 3: Gulf of Mexico, Corpus Christi

Site 3 shows a similar trend in results as Site 1. For an SES with a yearly rate of 4.5 M\$/year, the SOV becomes competitive with a price lower than 8.5 M\$/year. However, this price is not currently available in the market. Thus, for this site, the SES remains the most cost-efficient solution. If the SES has a yearly rate of 2.7 M\$/year, the SOV should have an even lower price (i.e., 6.5 M\$/year). Figure 15 and Figure 16 show the sensitivity results (cost per kWh and total O&M cost) on the SOV and SES prices for Site 3.

Figure 15: SOV vs. SES fixed yearly prices sensitivity study for site 3 (Cost per kWh)

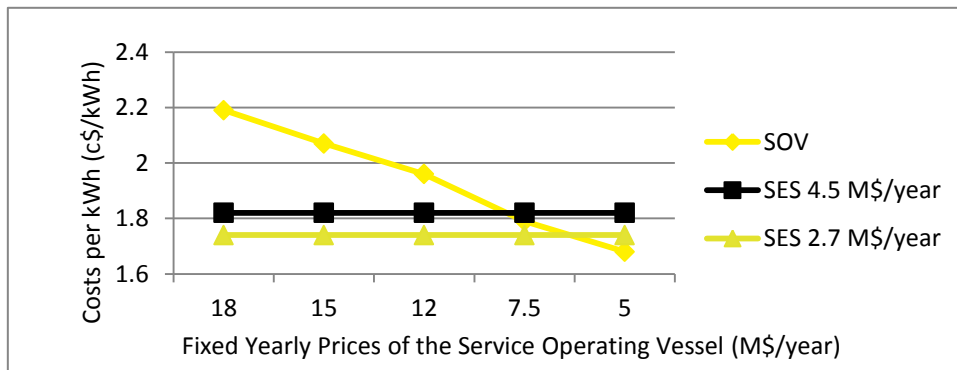
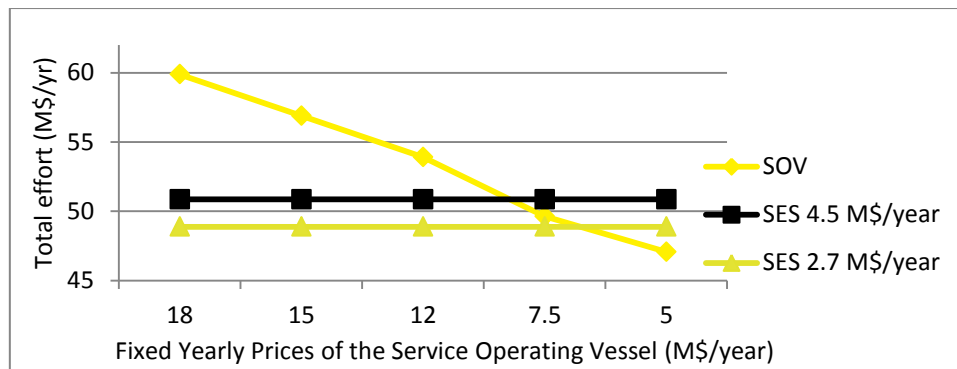


Figure 16: SOV vs. SES fixed yearly prices sensitivity study for site 3 (Total O&M Costs)



6.2 Extreme Weather Challenges (Hurricanes)

Some sites in this report show strong tendencies toward hurricanes. As mentioned in Section 3, Site 1, 2, and 3 have the potential for tropical storms and hurricanes. To take into account the effect of hurricanes, some sensitivity studies were performed. First, it was assumed that the hurricanes would increase the failure rates of some of the wind turbine components. The impact of this increase to O&M KPIs is evaluated in this section. Second, a study that evaluates an additional preventive maintenance task that aims to compensate this increase was conducted.

6.2.1 Model Inputs Changes

Failure Rate Increase

To take into account the effect of hurricanes, the changes in the failure rate of the wind turbine components were made. Based on *The Saffir-Simpson Hurricane Wind Scale* [34], hurricanes occur when the wind speeds are above 33 m/s. In this situation, the wind turbine has reached its cut-out wind speed limit resulting in no operation. Moreover, it is assumed that during the hurricane period, only the outer components would be affected. These components are the rotor blade, the blade adjustment or pitch system, and the turbine structure: the tower and foundation. For this sensitivity study, the failure rates are increased for all these components simultaneously by 5%, 10%, 15%, and 20%⁸. Table 25 shows the calculated increase in failure rates.

Table 25: Failure Rate Changes for the Components

Failure Rate Components	Original	+5%	+10%	+15%	+20%
Foundation/Scour Protection	3.37	3.54	3.71	3.87	4.04
MDC Blade Adjustment	0.81	0.86	0.90	0.94	0.98
UMD Turbine Structure/Tower	0.16	0.17	0.18	0.18	0.19
MDA10 Rotor System - Blades	0.07	0.07	0.07	0.08	0.08

Calendar-Based Maintenance Post-Hurricane Period

With continuous operation over the course of years, hurricanes might damage the above-mentioned components. To reduce this effect and prevent worsening the conditions, some preventive maintenance is needed. This sensitivity case aims to evaluate if adding a post-hurricane calendar-based maintenance would compensate the increase in failure rates of the impacted components despite the higher maintenance or repair cost investments. Thus, a case implementing calendar-based maintenance for only the impacted components was performed. The maintenance requires three technicians working for 6 hours, performing some inspection and small replacements with 10 k\$ spare parts.

For this case, a 20% increase in failure rates in the impacted components is assumed. For the first case, it is assumed that adding calendar-based maintenance would reduce the failure rate to 10%. For the second case, the additional calendar-based maintenance would reduce the failure rate of these components to 5%.

6.2.2 Results

Failure Rate Increase

The O&M cost increases with the decrease of the mean time to failure, or increase of the failure rate. This increase follows a linear trend given by the equation shown in Figure 43 and Figure 44 in Appendix D.1. An increase of 20% of the failure rate leads to an increase of approximately 5% of the cost per kWh. For the sensitivity study on hurricane effects, an increase of 20% of the failure rate on the impacted components as a result of hurricanes was assumed. Table 26 lists the results of this sensitivity study.

⁸ This study acknowledges that there is significant uncertainty regarding the actual impacts of hurricanes and that MMTF may or may not be the best way to think about the impact of hurricanes on offshore wind farms. Further investigation is required.

Table 26: O&M KPIs Obtained in Hurricane – Components Failure Rate Sensitivity Study

Failure Rate	Time-based Availability (%)	Yield-based Availability (%)	Costs per kWh (c\$/kWh)	Repair Costs (M\$/yr)	Revenue Losses (M\$/yr)	Total O&M costs (M\$/yr)
Original	95.4	95.4	1.81	45.29	5.28	50.57
+ 5%	95.4	95.4	1.84	45.91	5.31	51.22
+ 10%	95.4	95.4	1.85	46.41	5.26	51.67
+ 15%	95.3	95.3	1.89	47.23	5.36	52.59
+ 20%	95.3	95.3	1.91	47.65	5.41	53.06

Calendar-Based Maintenance Post-Hurricane Period

The assumption considered in the sensitivity analysis is that the failure rates of the impacted components is reduced by 10% or 15% when calendar-based maintenance was simulated. The results show that the O&M cost reduction is not significant (0.52% for a 10% reduction and 1.57% for a 15% reduction). According to this model, adding a post-hurricane period for calendar maintenance is not an effective strategy. The costs to perform the task are higher than the cost reduction provided by the decrease of the failure rates. Table 27 shows the post-hurricane calendar-based maintenance sensitivity results.

Table 27: O&M KPIs with Post-Hurricane Calendar-Based Maintenance

SES	Hurricane Case Failure Rate Increased by 20%	Post-Hurricane Maintenance Failure Rate Decrease of 10%	Post-Hurricane Maintenance Failure Rate Decrease of 15%
Time-based Availability (%)	95.3	95.3	95.2
Yield-based Availability (%)	95.3	95.3	95.3
Costs per kWh (c\$/kWh)	1.91	1.9	1.88
Repair Costs (M\$/yr)	47.65	47.54	47.06
Revenue Losses (M\$/yr)	5.41	5.35	5.45
Total O&M Costs (M\$/yr)	53.06	52.88	52.51

6.3 Availability of Vessels for Replacement

This study was conducted on the most suitable strategy for Site 2 (Kitty Hawk). However, the method and results are also applicable to other U.S. wind farms that are still leasing vessels from Europe. In the subsections below, the steps to model the impact of in-house manufacturing replacement vessels (jack-up barge) in the United States are discussed.

6.3.1 Model Inputs Changes

Removal of the U.S.-flagged jack-up barge

To comply with the Jones Act, a U.S.-flagged support barge was used (in the baseline scenario) to perform operations between the harbor and wind farm. It is mainly used to load and unload the large spare parts needed. Nevertheless, if the vessels for replacement are manufactured in or owned by the United States, this kind of support barge would not be required anymore.

Decrease of jack-up barge daily price

Under the assumption that the jack-up barge is manufactured in the United States, it is possible to consider that the daily price of this vessel will be in the same range as European leasing prices, which are between 70k€ and 80k€ per day. To take this parameter into account, the price of the

jack-up barge is reduced from 140 k\$/day to 70 k\$/day. Thus, the daily waiting price is also decreased from 98 k\$/day to 52.5 k\$/day.

Decrease of mobilization time

Manufacturing the jack-up barge directly in the United States would also reduce the mobilization time from 720 hours (as assumed in the baseline scenarios) to 360 hours, as well as reduce the mobilization price from 1 M\$/mob to 0.75M\$/mob.

Assumption of a cable-laying vessel manufactured in the United States

Another assumption considered is that the cable-laying vessel was manufactured in the United States. Thus, the mobilization time is reduced from 720 hours to 360 hours, respectively, and the mobilization time is reduced from 5.05 M\$/mob to 0.48 M\$/mob.

6.3.2 Results

Effect of the in-house jack-up barge

Removing the U.S.-flagged jack-up barge in the model reduces the O&M costs by 19%. This cost reduction can be achieved if the jack-up barge is manufactured in the United States. Furthermore, if the price of jack-up barges used in the United States are approximately at the same price as in the European market, then the O&M costs decrease by 28%.

Manufacturing the jack-up barge directly in the United States also reduces the mobilization time, from 720 hours to 360 hours, and consequently, the mobilization price. Unexpectedly, reducing the mobilization time increases the overall costs. Despite the increase, the overall benefits of using in-house vessels are significant.

Table 28 shows the results of the Jones Act compliance case studies.

Table 28: O&M KPIs of the Jones Act Compliance Cases (Jack Up Barge)

	Case ⁹ Control	Case 1 ¹⁰	Case 1 ¹⁰ % diff	Case 2 ¹¹	Case 2 ¹¹ % diff	Case 3 ¹²	Case 3 ¹² % diff
Time-based Availability (%)	95.7	95.8	0.10	95.8	0.10	96	0.31
Yield-based Availability (%)	95.8	95.8	0.00	95.8	0.00	96	0.21
Costs per kWh (c\$/kWh)	2.33	1.89	18.88	1.68	27.90	1.73	25.75
Repair Costs (M\$/yr)	49.92	40.55	18.77	36.06	27.76	37.14	25.60
Revenue Losses (M\$/yr)	4.01	3.97	1.00	3.99	0.50	3.77	5.99
Total O&M Costs (M\$/yr)	53.93	44.52	17.45	40.04	25.76	40.92	24.12

Effect of the in-house cable-laying vessel

The effect of the U.S.-manufactured cable-laying vessel was also evaluated. After applying all the aforementioned scenarios and assuming that the cable-laying vessel comes from the United States, the cost of electricity is reduced by 1.15%, which represents a savings of 0.34 M\$/yr. Considering a wind farm lifetime of 20 years, the total amount of money saved is 6.8M\$. For that reason, the reduction is not as significant as expected. Certainly, the usability of a cable-laying vessel is less than a jack-up barge. To judge the overall benefit of manufacturing cable-laying

⁹ Case control: SOV in Site 2 – Kitty Hawk

¹⁰ Case 1: U.S.-flagged support barge removal

¹¹ Case 2: U.S.-flagged support barge removal + decrease of the jack-up barge daily price

¹² Case 3: U.S.-flagged support barge removal + decrease of the jack-up barge daily price and mobilization time

vessels in the United States, the total savings throughout an offshore wind farm has to be compared with the costs of the development of the industry.

Table 29: O&M KPIs of the Jones-Act-Compliance Cases (Jack-Up Barge + Cable-Laying Vessel)

	Case Control ⁹	Case 4 ¹³	Case 4 ¹³ % diff
Time-based Availability (%)	95.7	96	0.31
Yield-based Availability (%)	95.8	96.1	0.31
Costs per kWh (c\$/kWh)	2.33	1.73	25.75
Repair Costs (M\$/yr)	49.92	37.03	25.82
Revenue Losses (M\$/yr)	4.01	3.74	6.73
Total O&M Costs (M\$/yr)	53.93	40.77	24.40

General conclusion

With U.S.-manufactured vessels, the annual cost reduction under all the assumptions described in this report is around 11 M\$/yr. For 20 years of operation, the amount of money saved is 220 M\$, which represents almost 25% of the total O&M costs. However, these savings need to be compared to the capital investment in the development of a jack-up barge.

6.4 Different Parameter Used for Electricity Price

This sensitivity analysis was conducted to evaluate the influence of electricity prices. In this case, LCOE was used instead of LACE, and the study was only performed on Site 1. However, this method can be applied to all of the sites, and the results can be extended.

6.4.1 Model Inputs Changes

The LCOE represents the cost (in U.S. dollars) per kilowatt-hour of building and operating an electric-generating plant over an assumed financial life and duty cycle. The values used are extracted and interpolated over five years from a study done by NREL [31]. The values are presented in Table 30.

Table 30: Electricity Prices Input for the 5-Year Simulations (Applicable to Site 1)

Year	LCOE (2015\$/kWh)
2022	0.135
2023	0.130
2024	0.126
2025	0.122
2026	0.118

6.4.2 Results

The choice of electricity prices is critical for the accurate estimation of revenue losses and total O&M costs. As explained in Section 4.1.1, the baseline cases used LACE as an electricity price

¹³ Case 4: U.S.-flagged support barge removal + decrease of the jack-up barge daily price and mobilization time + cable-laying vessel manufactured in the U.S.

parameter. The results shows that revenue losses with LACE are much less than the revenue losses using LCOE because the LACE price is less than the LCOE. From this result, it can be concluded that electricity price directly impacts the revenue losses. However, the choice of electricity prices does not impact the repair or direct costs. As a sum of those two costs—revenue losses and repair costs—total O&M costs are also impacted with the choice of electricity prices. Figure 17, Figure 18, and Figure 19 show the comparison of O&M KPIs using LACE and LCOE for Site 1.

Figure 17: Cost-per-kWh comparison between LACE and LCOE for Site 1

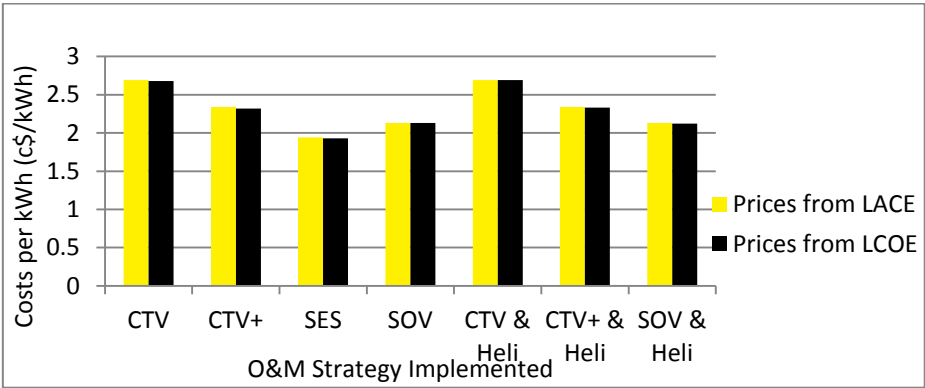


Figure 18: Revenue losses comparison between LACE and LCOE for Site 1

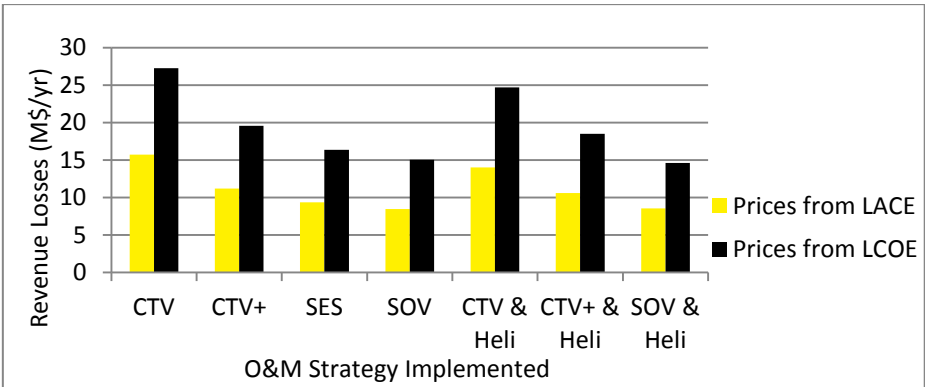
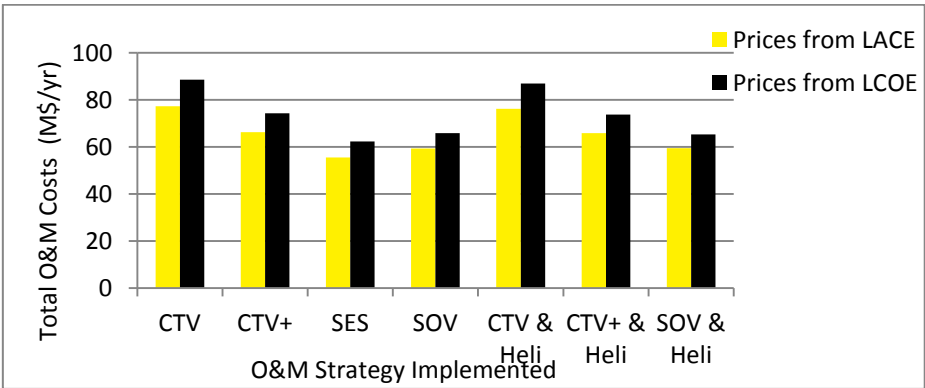


Figure 19: Total O&M costs comparison between LACE and LCOE for Site 1



7. U.S. and European Wind Farms Comparison Study

This section describes a comparison study on maintenance strategies between U.S. and European wind farms. To compare these maintenance strategies, a similar site in Europe with comparable characteristics was chosen. First, the average metocean data were compared. From there, some conclusions have been drawn to understand the particular location challenges of offshore wind farms in the United States. The next step was to find an existing European wind farm with an already defined O&M strategy.

7.1 Europe Wind Farm

In this report, the Gemini wind farm was chosen to be compared with U.S.-prospective wind farms. Gemini is a fully commissioned Netherlands' Offshore Wind Farm located 85 km from the shore. Like Sites 1-3, the total capacity is 600 MW, but the wind farm consists of 150 4-MW wind turbines. The average water depth in this area is around 30 m. With these characteristics, Gemini has similar characteristics to the New York and Gulf of Mexico sites.

The average wind speed and wave height for the Gemini wind farm are presented in Table 31. From these data, it is known that except for the Pacific site, the average values of the metocean condition in Gemini are higher than in the United States. Furthermore, based on the workability graph shown in Appendix C, Gemini has a similar profile to New York (Site 1). Therefore, Site 1 was chosen to be U.S. site to be compared with the Gemini wind farm in Europe.

Table 31: Average Wind Speed and Wave Height for the Gemini Wind Farm

Metocean Parameters	Annual			
	Average	Minimum ¹⁴	Maximum ¹⁵	Standard Deviation
Wind Speed (at a 100-m hub height); (m/s)	9.48	0	34.93	5.09
Significant Wave Height (m)	1.55	0.02	9.10	0.98

¹⁴ Minimum value in given year of data sets

¹⁵ Maximum value in given year of data sets

7.2 Model Changes

The ECN O&M Calculator was used to simulate the Gemini wind farm with the strategy that is being applied at the wind farm today. The Gemini project currently has an SOV as its primary access vessel, with support from a daughter craft for technicians transfer and a helicopter for a summer, calendar-based maintenance campaign and during peak period or emergency situations [35].

For this comparison study, it was assumed that all U.S. and European vessels have the same capability and weather limitation. Following are the list of changes considered in this comparison study.

General Input Changes

The electricity price used is a constant value of 0.13\$/kWh instead of the LACE. The weather data used was the one recorded for the Gemini wind farm from 1992 to 2011.

Equipment Changes

As vessels for replacement are already available in Europe, the working price of the jack-up barge was decreased from 140 k\$/day to 70 k\$/day. Thus, the daily waiting price was also lowered from 98 k\$/day to 52.5 k\$/day. Consequently, the mobilization time was decreased from 720 to 360 hours and the mobilization price was reduced from 1,000k\$/mob to 750 k\$/mob. The diving support vessel mobilization price was reduced from 975 k\$/mob to 160 k\$/mob. The cable-laying vessel mobilization time was reduced from 720 to 360 hours and the mobilization price from 5.050 k\$/mob to 480 k\$/mob. The U.S.-flagged support barge used to comply with the Jones Act in the United States was consequently removed from the model.

Wind Farm Adaptation

One hundred 6-MW wind turbines in the NREL simulation were replaced by 150 4-MW wind turbines in the Gemini simulation.

7.3 Results and Discussion

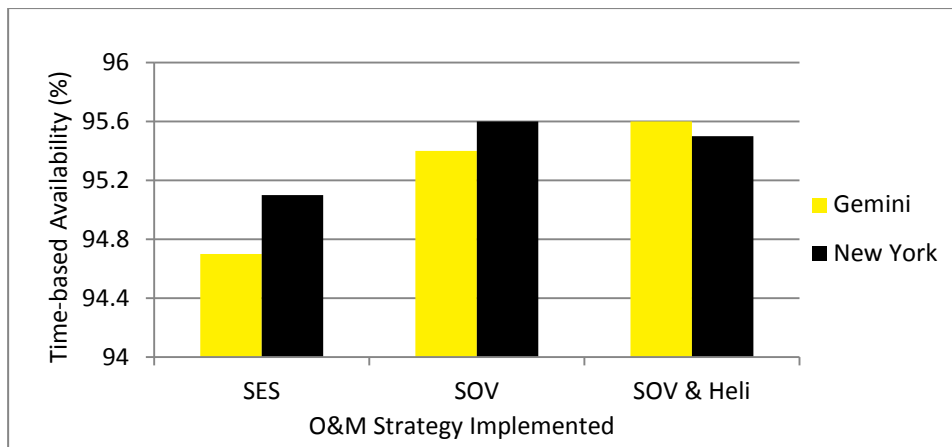
In this section, the O&M KPIs between the modelled Gemini and Site 1 are compared. The differences of both availability and costs are discussed.

Availability Comparisons

The expected availability of Site 1 is higher than for the Gemini. This outcome can be explained by the relatively milder meteocean conditions at Site 1 (7.5% lower average wind speed and 18% lower average wave height).

With the Gemini wind farm, only two strategies achieved the availability target, using an SOV and an SOV with an additional helicopter if required. In the Gemini model, the SOV and helicopter strategy provides higher availability of 0.2% compared to the strategy that only uses an SOV. Therefore, for the Gemini, the SOV with the support of a helicopter is the most suitable strategy if the selection is only based on the availability. On the other hand, for Site 1, an SES also allows the wind farm to achieve the availability target, which is 95%. Figure 20 shows the calculated availability comparison between the Gemini wind farm and Site 1.

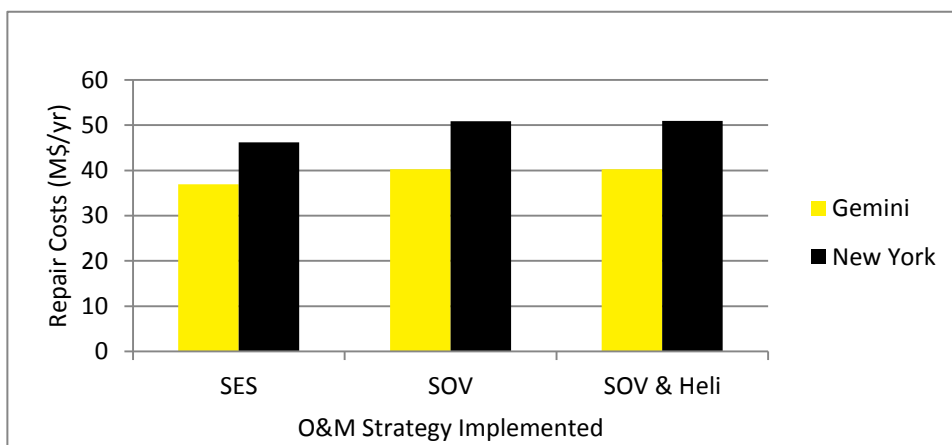
Figure 20: The Gemini wind farm vs. Site 1 (New York) availability comparison



Repair Cost Comparison

As a consequence of the unavailability of the vessels for replacement in the United States, the repair costs are higher (by 21%) for an SOV and helicopter strategy. This important difference is explained partly by the additional costs of using U.S.-flagged support barges, which is a requirement of operating a wind farm that is compliant with the Jones Act. Figure 21 shows the calculated repair costs comparison between the Gemini wind farm and New York site.

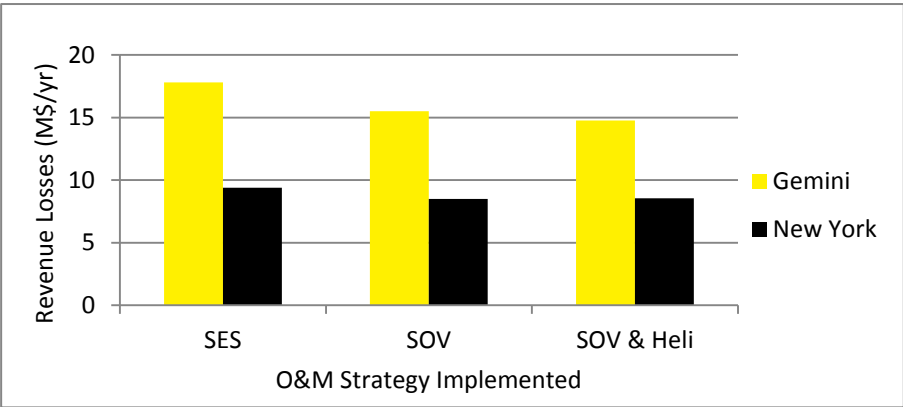
Figure 21: Gemini vs. New York repair cost comparison



Revenue Losses Comparison

The comparison of revenue losses shows significant divergences between the United States and Europe. Indeed, the electricity prices used for the simulation were different. For New York, the LACE price was used: 0.071 c\$/kWh, instead of 0.13 c\$/kWh for the Gemini wind farm. This 45% difference in the input can explain the 50% lower costs obtained in New York. More details on the impact of the electricity prices are given in the Section 6.4. Figure 22 shows the revenue losses comparison between the Gemini wind farm and New York site.

Figure 22: Gemini vs. New York revenue losses cost comparison



Costs Comparison

Finally, this subsection explains the differences in cost per kilowatt-hour and total O&M costs between the Gemini wind farm and Site 1. Both sites have a similar trend of both mentioned costs for all strategies. However, Site 1 has higher costs, which is caused by higher repair costs due to the unavailability of vessels for replacement and the additional U.S.-flagged support barge. The result comparisons are presented in Figure 23 and Figure 24.

Figure 23: Gemini vs. New York cost per kilowatt-hour losses cost comparison

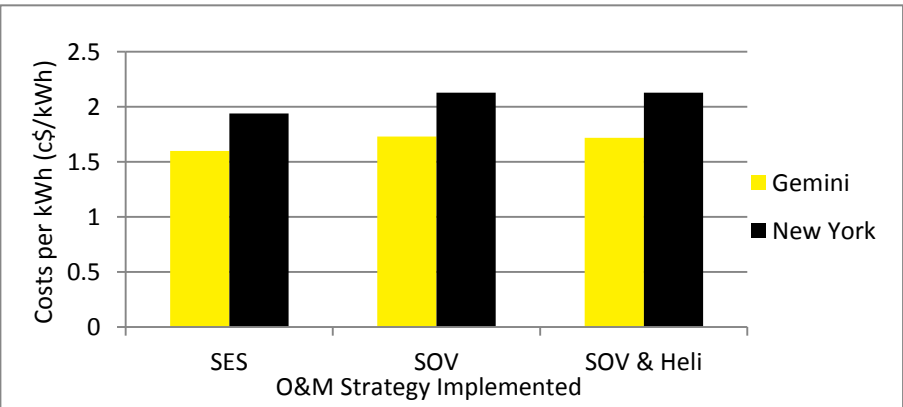
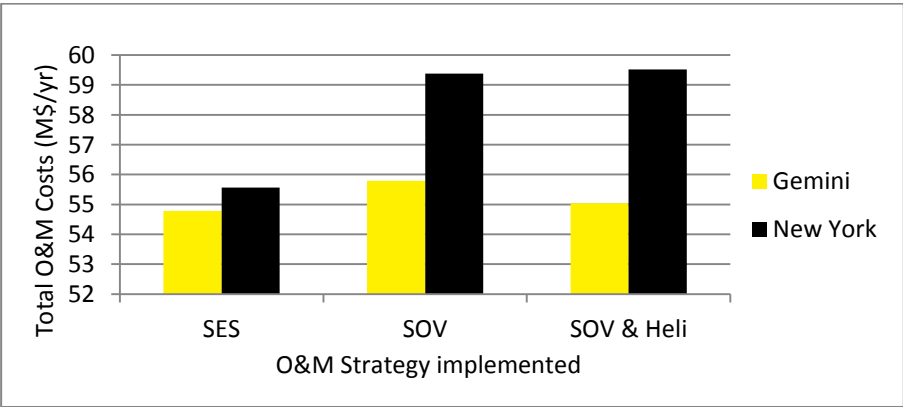


Figure 24: Gemini vs. New York total O&M cost comparison



8. Conclusion



8.1 Summary of Findings

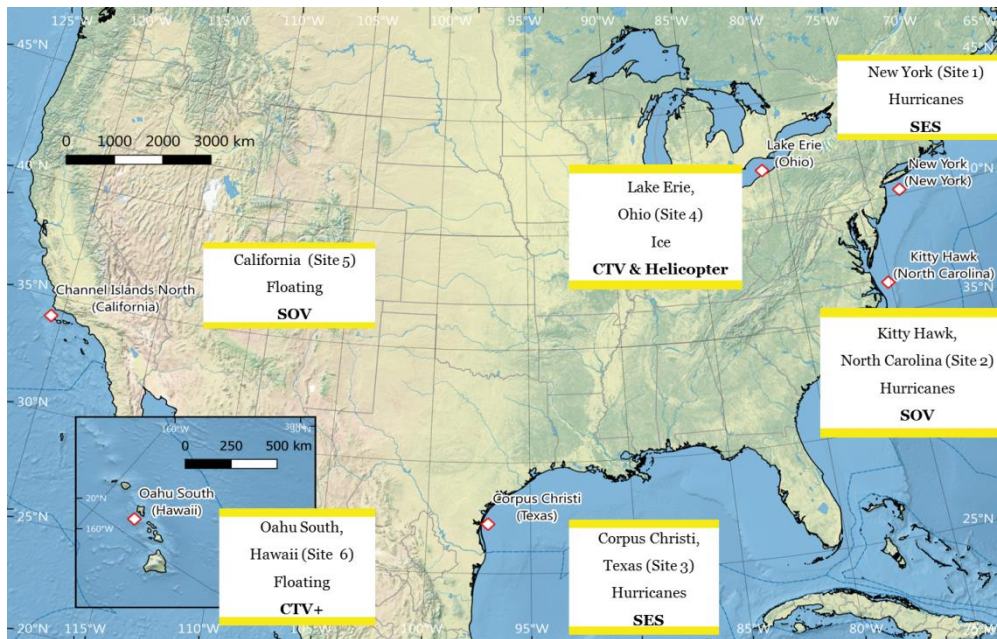
The main objective of this study is to optimize the O&M strategy for six prospective offshore wind sites in the United States in order to minimize O&M costs and maximize availability. The study demonstrates the need for a dedicated O&M strategy for each site based on its unique characteristics and metocean conditions. These strategies are strongly dependent on individual site characteristics such as distance to shore, water depth, location challenges, and metocean conditions, including wind and wave climate.

As shown in Table 32, the most suitable O&M strategies for the sites differ based on the wind farm characteristics. The metocean conditions, including distance from shore, are a critical driver for O&M strategy. For near-shore wind farms, similar to sites in Ohio and Hawaii, two crew transfer vessels are sufficient to maintain the wind farms. The OPEX of site Hawaii is 1.35 c\$/kWh using two CTV+. Additionally, as discussed in section 5.4 for the Ohio site, if ice is present for offshore wind applications in fresh water then a helicopter can be used to increase accessibility to the wind farm for inspections and small repairs, ultimately increasing availability. The OPEX of the Ohio site is 4.27 c\$/kWh using two CTV and a helicopter when needed. The OPEX of this site is higher than the other 5 sites because of the long waiting time while the ice is present and the lower power produced (345 MW capacity).

On the other hand, far-shore wind farms similar to sites in New York, North Carolina, Texas, and California require vessels that have higher technician capacity, faster transit speeds, more resilience to harsher metocean conditions, and the capability to stay out at sea for longer durations. Therefore these sites utilize surface effect ships and service operation vessels to keep O&M costs low and maintain high wind farm availability. The OPEX of these sites are 1.94 (New York), 2.33 (North Carolina), 1.82 (Texas), and 1.31 (California) c\$/kWh. A summary of the most suitable strategy for the six wind farms selected is shown in Table 32 and Figure 25.

Table 32: Summary of the O&M KPIs of the Chosen Strategies

Sites	Name of the Site	Characteristics	Most Suitable Strategy	Time-based Availability (%)	Yield-based Availability (%)	Cost per kWh (c\$/kWh)	Total O&M Cost (M\$/year)
1	New York	600 MW (100*6 MW) 70 km from Leonardo State Marina Harbour; 20-40 m deep	SES	95.1	94.8	1.94	55.56
2	North Carolina	600 MW (100*6 MW) 143 km from Newport News Harbor; 300 m deep	SOV	95.7	95.8	2.33	53.93
3	Texas	600 MW (100*6 MW) 102 km from Corpus Christi Harbor; 25 m deep	SES	95.3	95.3	1.82	50.86
4	Ohio	345 MW (100*3.45 MW) 32 km from Ashtabula Harbor; 22 m deep	CTV & Helicopter	93.3	92.9	4.37	45.62
5	California	600 MW (75*8 MW) 127 km from Hueneme Harbour; 575 m deep	SOV	95.2	95	1.31	45.94
6	Hawaii	400 MW (50*8 MW) 38 km from Honolulu Harbour; 700 m deep	CTV +	95.8	95.7	1.35	41.49

Figure 25: The most suitable O&M strategy for the six reference wind farms

For the specific case of conducting large-component replacements, the vessels and equipment differ based on the wind farm location and site characteristics. Shallow-water sites, similar to sites in New York, North Carolina, Texas, and Ohio, utilize high-capacity jack-up barges. Conversely, for deep-water sites, similar to sites in California and Hawaii, a jack-up barge cannot be used since the water depths exceed the length of the jack-up legs. Instead, the floating turbines are towed to port for repair using towing vessels .

A challenge for the United States is the lack of available heavy-lift boats capable of carrying replacement large-turbine components. Similarly, the cable laying vessels for cable replacement are not available. Hence, it is assumed that the United States requires chartering these vessels from foreign countries (Europe in this study), which can cause a significant increase in O&M costs. For example, if it is assumed that all vessels are chartered from within country, the annual O&M

cost reduction is around \$11 million per year. This is significant savings of approximately \$220 million for a wind farm operating for 20 years, representing almost 25% of the total O&M costs (see chapter section 6.3.2). A developed and robust U.S. supply chain is not only beneficial to lowering the O&M costs but also is expected to reduce costs for turbine installations. Moreover, as the offshore wind industry continues to mature and the cost trends continue downward, new job opportunities are expected to emerge. As part of the study, sensitivity analysis regarding environmental conditions (e.g., hurricanes and icing conditions) is performed. The sensitivity to hurricanes is assumed to increase the failure rates of exterior turbine components. A 20% increase of failure rate on the turbine's exterior components leads to an O&M cost increase of approximately 5% on a cost-per-kilowatt-hour basis. As the offshore wind industry starts to develop projects in hurricane-prone regions the development of more hurricane-resilient wind turbines is expected to occur. In this case, additional costs incurred by these extreme weather conditions are expected to increase the turbine's capital costs (i.e., more expensive hurricane resilient turbines will transfer costs from operational to capital costs). However, investing in research and development (R&D) to create more hurricane-resilient wind turbines is anticipated to keep down O&M costs and achieve lower LCOE estimates for hurricane-prone regions.

The fresh water found in the Great Lakes region of the United States may have a tendency toward icing conditions in the winter months. In this study, these icing conditions are assumed to decrease or eliminate the accessibility of the maintenance vessel to the wind farm using a CTV. Assuming that ice is present for an average 11 weeks per year (based on data series mentioned in section 3.3), the time-based availability of the wind farm can be reduced up to 5%. Two potential solutions are investigated to access the turbines during these 11 weeks for inspections and small repairs. The first solution considers a vessel capable of breaking through the ice to transport technicians to the wind farm and the second considers a helicopter. The ice-breaking vessel (which is readily available in the Great Lakes region) is assumed to be capable of accessing the wind farm when the lake is 50% covered by ice; however, this does not result in higher availability than using a CTV. With limited to no gain in wind farm availability, in addition to the higher cost of the ice-breaking vessel, the O&M costs are increased by about 10.4%. However, if you consider a helicopter strategy assuming access to the wind farm when the lake is 100% covered with ice, the results show a 3% increase in time-based availability and no impact on cost of electricity because the increase of repair cost is compensated with lower revenue loss. It is important to note that there are associated safety issues when transporting technicians using helicopters during the winter months, especially with the presence of ice. Caution should be taken if considering this type of O&M strategy.

Although Europe, especially the North Sea region, has experience and knowledge in O&M for offshore wind farms, the strategies employed cannot be exactly replicated in the United States. Specifically, the United States has various regional conditions, such as hurricanes and tropical storms in the Gulf of Mexico and Atlantic, icing conditions in the Great Lakes, and deep water in the Pacific, that need to be considered. Furthermore, the United States currently has a limited offshore wind supply chain that is anticipated to impact the O&M strategies utilized. These conditions stress the importance of developing a local supply chain that includes building a local offshore O&M vessel fleet. If the United States charts high-capacity jack-up barges from Europe to conduct large repairs instead of utilizing U.S.-flagged vessels the analysis shows an estimated 18%–20% increase in repair cost between similar wind farms in the United States and Europe (with that cost being higher in the United States). As a conclusion, between similar sites in Europe and the United States the O&M repair costs have only a 1%–1.5% difference (with the cost being higher in the U.S.).

8.2 Future Work

Further study on other aspects of the United States offshore wind farm is necessary to optimize the development of the future offshore wind farm. ECN recommends the following:

- Evaluate O&M aspects of other potential sites based on feedback from stakeholders in United States. This study only evaluated six potential locations for offshore wind. However, the active developers in the United States are exploring more wind farm sites of interest.
- Evaluate other more innovative O&M strategies.
- Study the installation aspects, estimating the planning, costs, and risks of different U.S. sites. This study concentrated only on the O&M aspects of U.S. offshore wind. However, the other major aspect of building the supply chain is the installation of these wind farms. The U.S. BOEM is currently conducting some studies to identify the logistics infrastructure of ports and vessels in the United States.
- Combine O&M and installation cost modelling to create an LCOE model for different sites. LCOE is a parameter by which a certain wind farm is evaluated. If the installation study is performed for the same wind farm as mentioned above, it can be combined with O&M to evaluate the overall LCOE of these wind farms. Moreover, additional sites can also be included.
- Study O&M strategies of offshore wind sites in Asia. ECN is currently doing research on sites in Japan and Taiwan.

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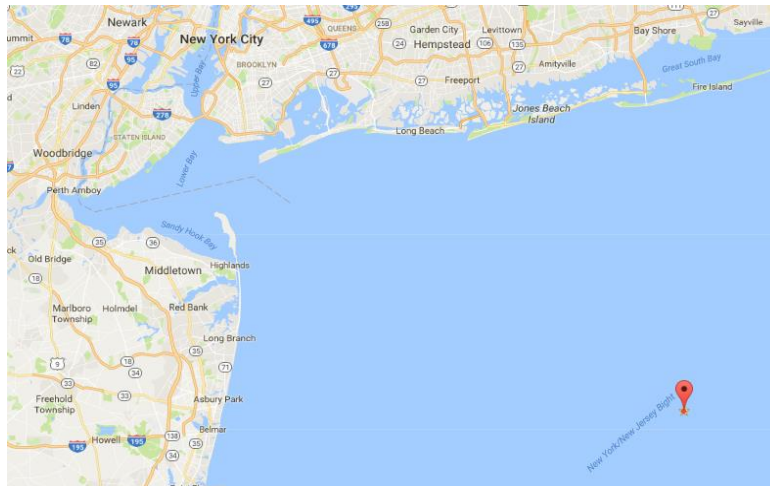
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Appendix A Site Maps

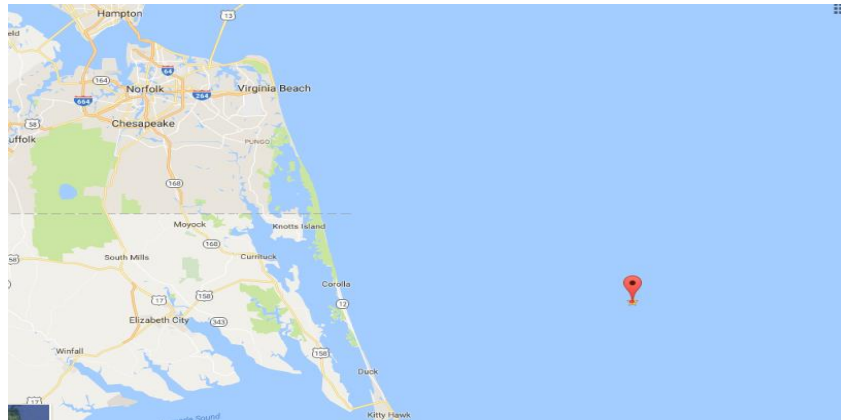
A.1. Site 1: North Atlantic, New York Wind Energy Area

Figure 26: Map of Site 1 (Lat: 40.204347 / Long: -73.195205)



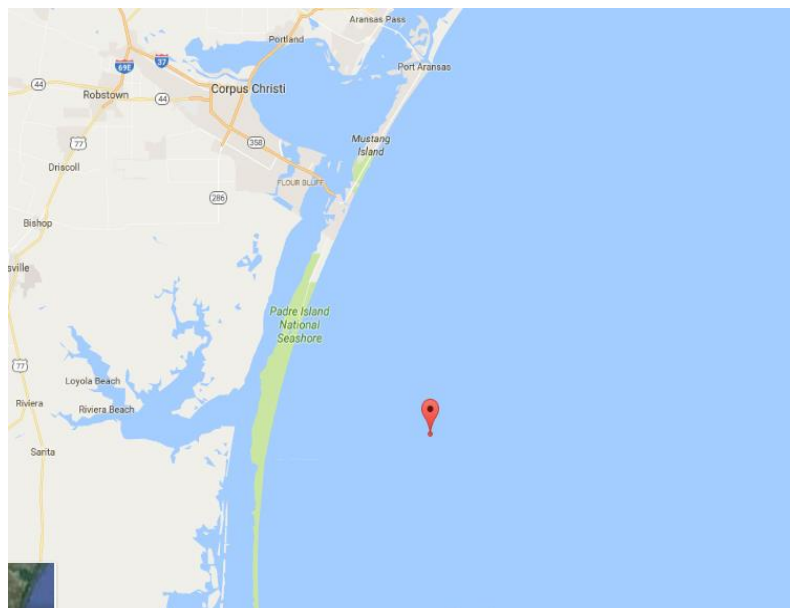
A.2. Site 2: North Carolina, Mid-Atlantic, Kitty Hawk Wind Energy Area

Figure 27: Map of Site 2 (Lat: 36.339 / Long: -75.128)



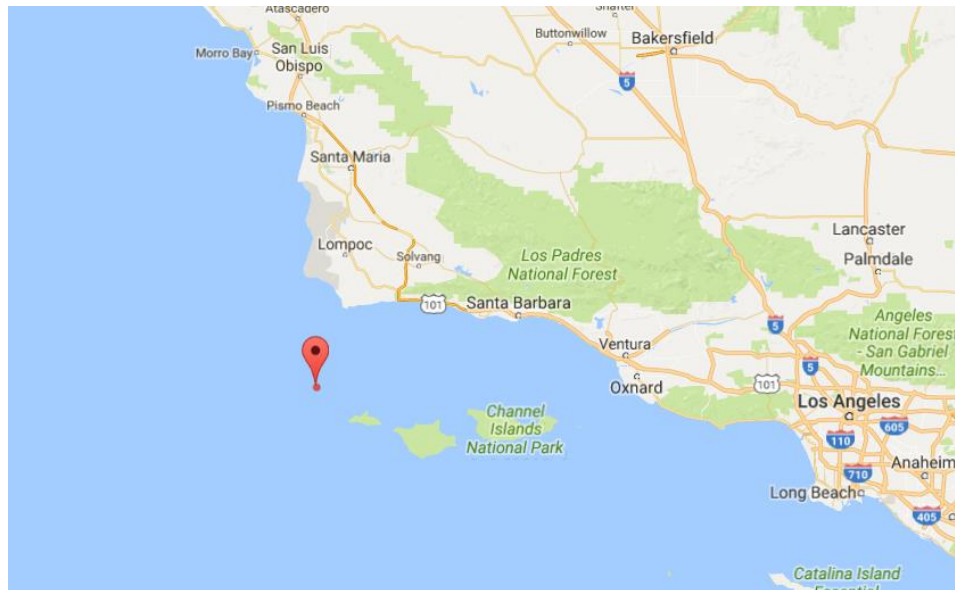
A.3. Site 3: Texas, Gulf of Mexico, Corpus Christi

Figure 28: Map of Site 3 (Lat: 27.25 / Long: -97.05)



A.5. Site 5 : California, Pacific, Channel Islands North

Figure 30: Map of Site 4 (Lat: 34.16, / Long: -120.59)



A.6. Site 6 : Hawaii, Oahu South

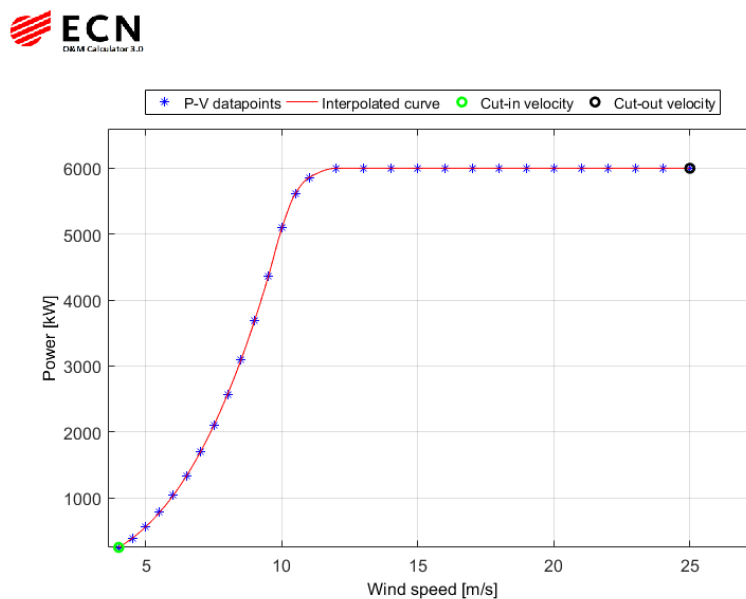
Figure 31: Map of Site 4 (Lat: 21.08 / Long: -158)



Appendix B Turbine Power Curve Graphs

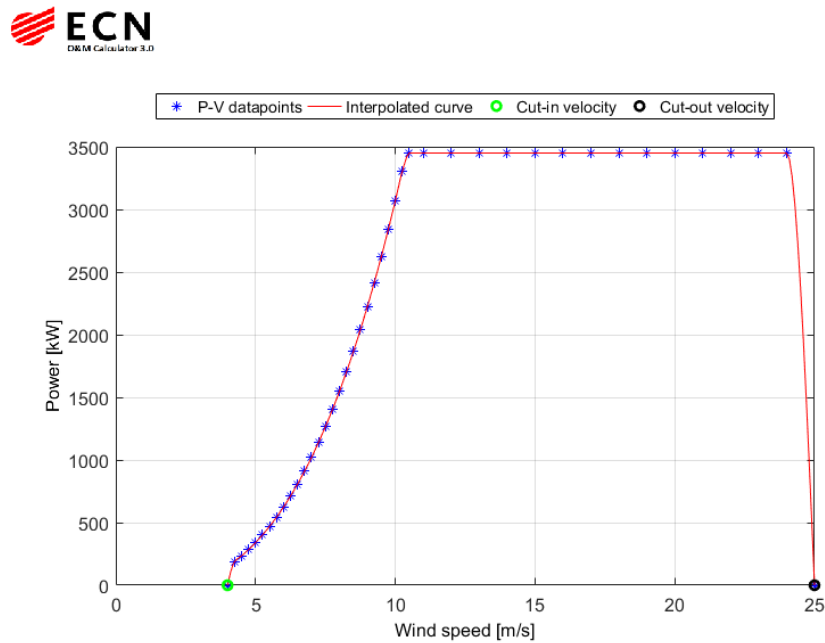
B.1 6 MW – Fixed-Bottom Substructure

Figure 32: The 6 MW – fixed-bottom power curve for Site 1, 2, and 3



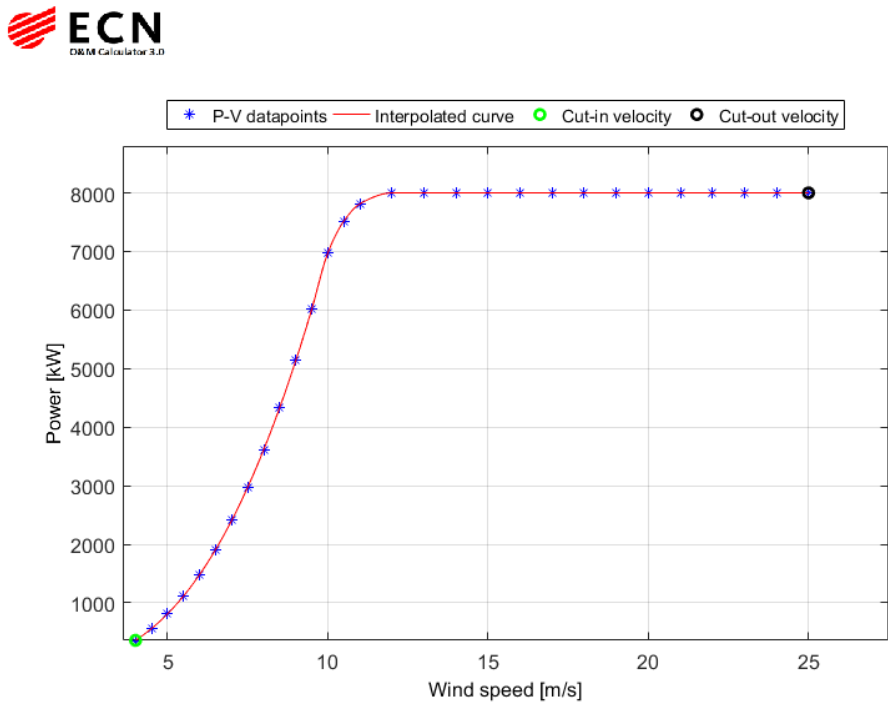
B.2 3.45 MW – Fixed-Bottom Substructure

Figure 33: 3.45 MW – Fixed-bottom power curve for Site 4



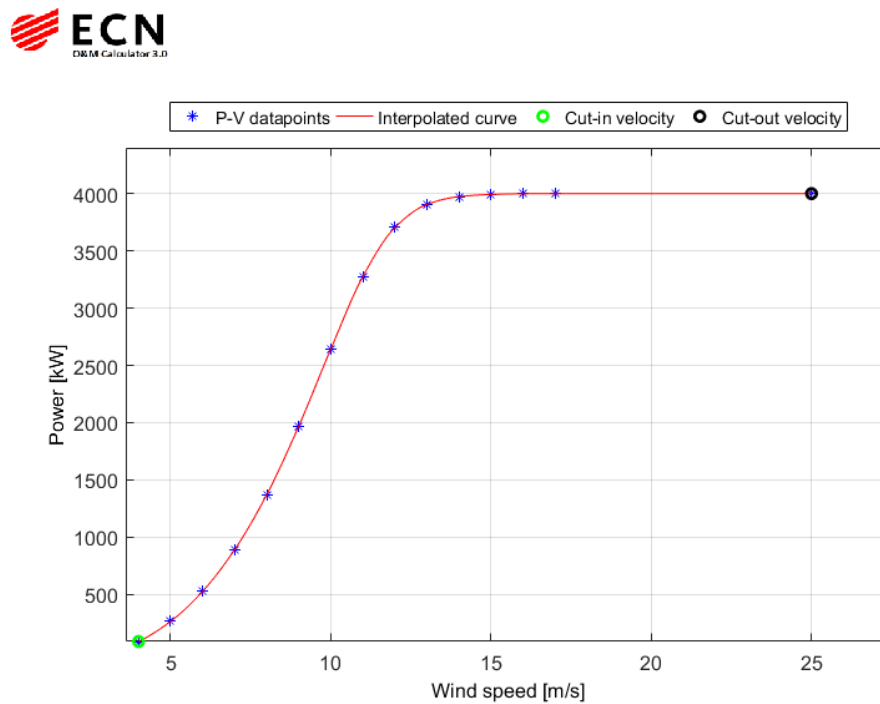
B.3 8 MW – Floating Substructure

Figure 34: 8 MW – floating power curve for Site 5 and 6



B.4 4 MW – Fixed-Bottom Substructure

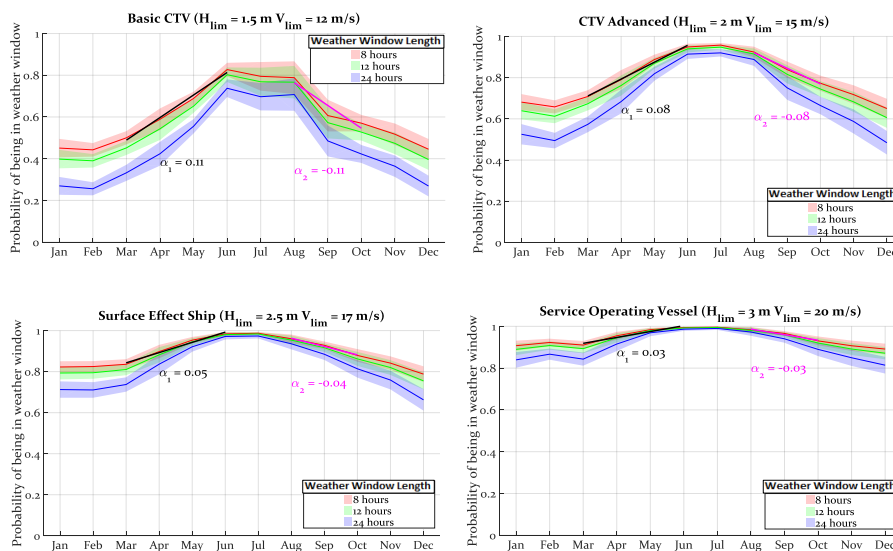
Figure 35: 4 MW – fixed-bottom power curve for the Gemini wind farm model



Appendix C Workability Graphs

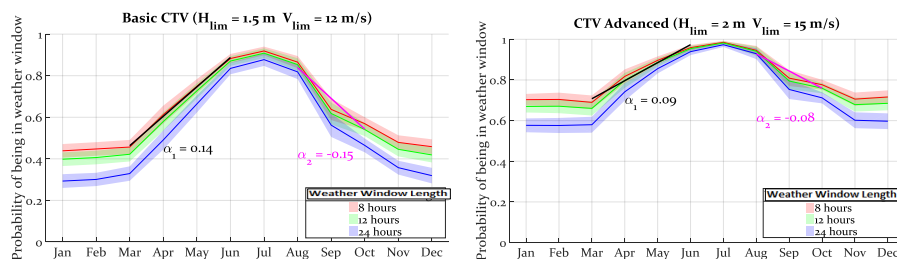
C.1 Site 1: North Atlantic, New York Wind Energy Area

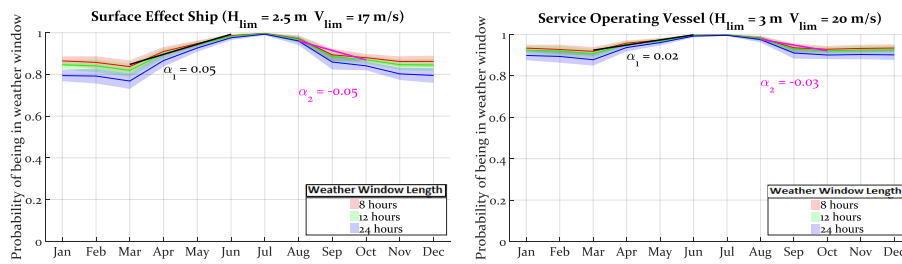
Figure 36: Workability graph for Site 1 (probability of various weather windows)



C.2 Site 2: Mid-Atlantic, Kitty Hawk Wind Energy Area

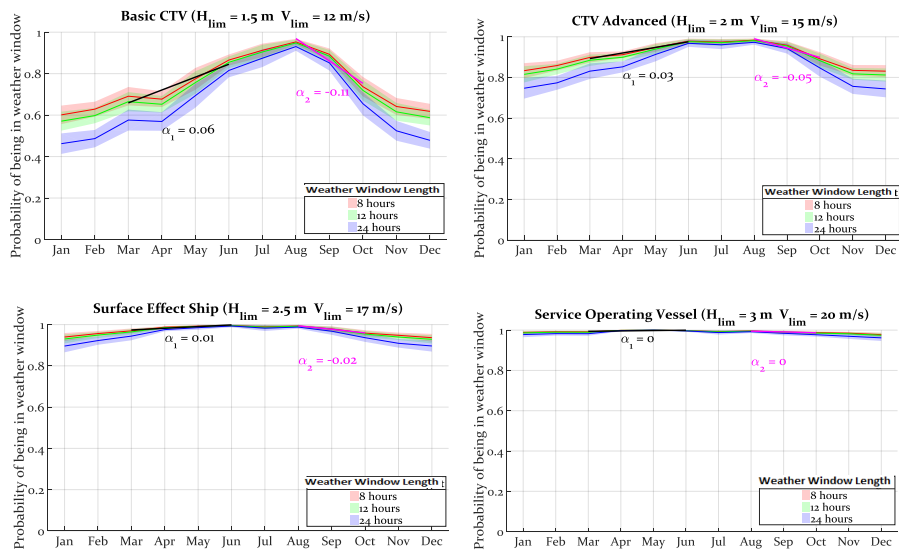
Figure 37: Workability graph for Site 2 (probability of various weather windows)





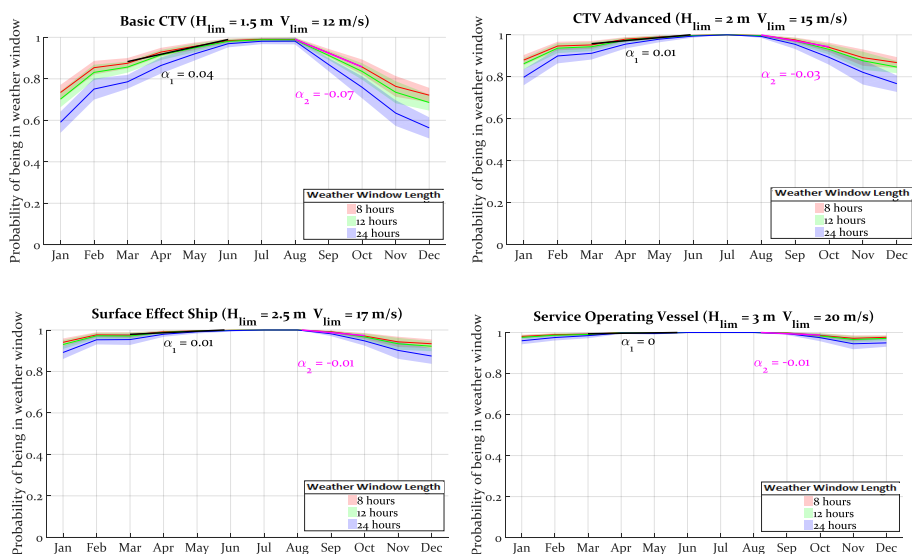
C.3 Site 3: Texas, Gulf of Mexico, Corpus Christi

Figure 38: Workability graph for Site 3 (probability of various weather windows)



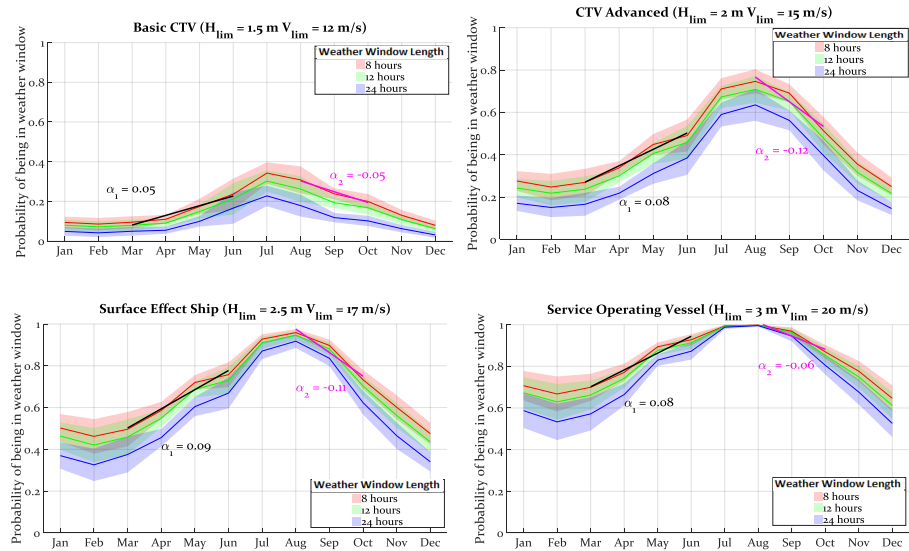
C.4 Site 4: Ohio, Great Lakes, Lake Erie

Figure 39: Workability graph for Site 4 (probability of various weather windows)



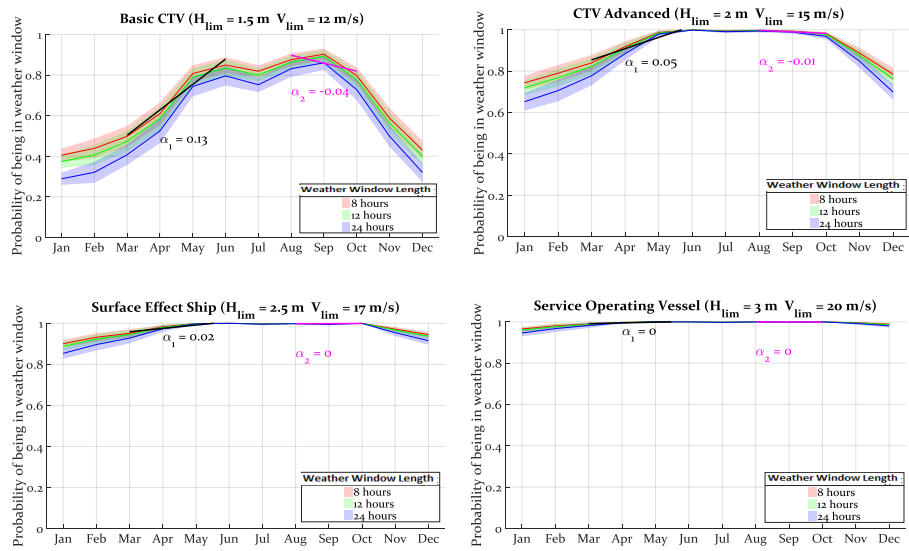
C.5 Site 5 : California, Pacific, Channel Islands North

Figure 40: Workability graph for Site 5 (probability of various weather windows)



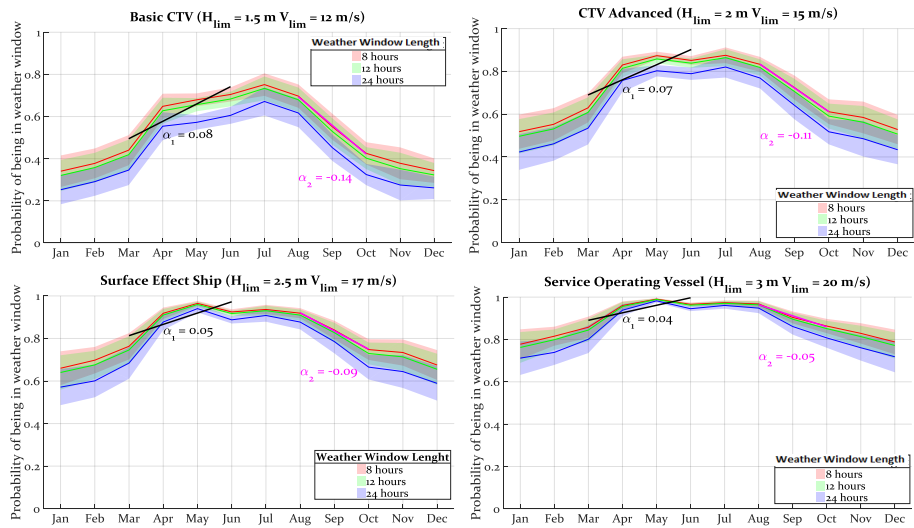
C.6 Site 6 : Hawaii, Oahu South

Figure 41: Workability graph for Site 5 (probability of various weather windows)



C.7 Gemini Wind Farm

Figure 42: Workability graph for the Gemini wind farm model (probability of various weather windows)



Appendix D Sensitivity Studies – Additional Graphs

D.1 Hurricane Study

Figure 43: Impact of hurricanes – increase of failure rate on the cost per kilowatt-Hou

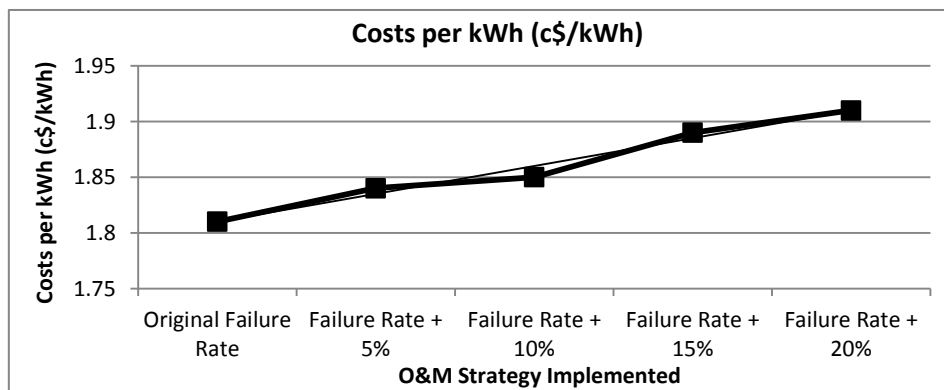
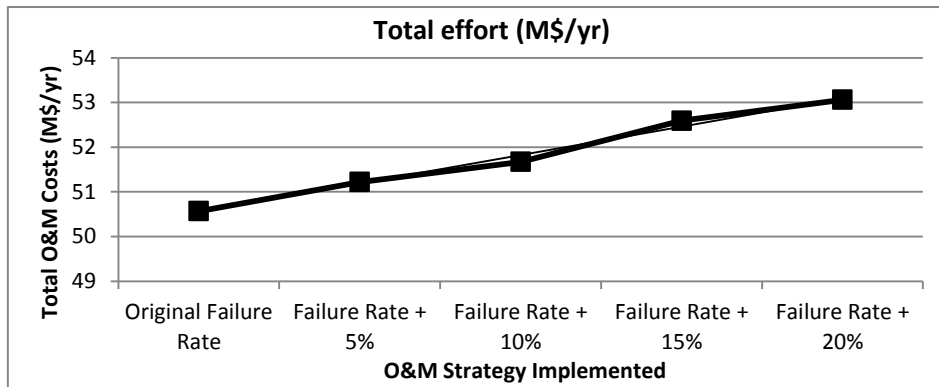


Figure 44: Impact of hurricanes – increase of failure rate of the Total O&M costs



D.2 Electricity Prices

Table 33:KPIs Comparison of Site 1 for Electricity Price Sensitivity Study

LCOE	Time-based Availability (%)		Yield-based Availability (%)		Costs per kWh (c\$/kWh)		Repair Costs (M\$/yr)		Revenue Losses (M\$/yr)		Total O&M Costs (M\$/yr)	
	LACE	LCOE	LACE	LCOE	LACE	LCOE	LACE	LCOE	LACE	LCOE	LACE	LCOE
CTV	91.9	92	91.2	91.4	2.69	2.68	62	61	16	27.3	77.4	88.7
CTV+	94.2	94	93.8	93.8	2.34	2.32	55	55	11	19.6	66.3	74.3
SES	95.1	95	94.8	94.8	1.94	1.93	46	46	9.4	16.4	55.6	62.3
SOV	95.6	96	95.3	95.2	2.13	2.13	51	51	8.5	15	59.4	65.9
CTV & Heli	92.6	93	92.2	92.2	2.69	2.69	62	62	14	24.7	76.3	87
CTV+ & Heli	94.4	95	94.1	94.1	2.34	2.33	55	55	11	18.5	65.9	73.7
SOV & Heli	95.5	96	95.2	95.4	2.13	2.12	51	51	8.6	14.6	59.5	65.4

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