Floating Offshore Wind Farms - Demand Planning & Logistical Challenges of Electricity Generation

by

Christopher Dozie Nnadili

B. Eng., Mechanical Engineering, Federal University of Technology Owerri, 2002
M.S., Mechanical Engineering, University of Missouri Rolla, 2005

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Signature of Author...
Master of Engineering in Logistics Program, Engineering Systems Division
May 8, 2009

Certified by...
Dr. Chris Caplice
Executive Director, Center for Transportation and Logistics
Thesis Supervisor

Accepted by...
Prof. Yossi Sheffi
Professor, Engineering Systems Division
Professor, Civil and Environmental Engineering Department
Director, Center for Transportation and Logistics
Director, Engineering Systems Division

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Abstract

Floating offshore wind farms are likely to become the next paradigm in electricity generation from wind energy mainly because of the near constant high wind speeds in an offshore environment as opposed to the erratic wind speeds in their onshore counterparts. By using floaters adapted from oilrigs, floating offshore wind farms can be operated with larger wind turbines for increased power generation.

In the United States, floating offshore wind farms located off the coast of New England would be near large load centers and accessible to transmission load lines with low capacity utilization. Apart from the technological challenges of building floating offshore wind farms stemming from the developmental stage of the floater technology, there are three major logistical challenges prospective operators would likely encounter in harvesting electricity. The first challenge is to understand the interaction between distances from shore to locate a wind farm given increasing wind speeds. The second challenge is to understand the marginal impact of distance from shore on revenue generated from electricity sales from a floating offshore wind farm. And finally the third challenge is to determine inventory policy for wind turbine components in operating a floating offshore wind farm given its more complex operation and maintenance schedule.

To address these challenges, this study examines a hypothetical 100 units of 5MW wind turbines to understand the economics of locating a floating offshore wind farm. It is important to know the intersection between the increase in revenue generated with distance from shore and increase in operation & maintenance costs of a floating offshore wind farm. Because there is currently no floating offshore wind farm at the time of this writing, estimated failure rate data was used to study demand patterns for offshore wind turbine components. Three of maintenance strategies were examined. The results obtained from this work will serve as a blue print for prospective operators of floating offshore wind farms in logistics planning and inventory management of wind turbine components for electricity generation.

Thesis Supervisor: Dr. Chris Caplice
Title: Executive Director, Center for Transportation and Logistics

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Most of all I would like to thank my family for their constant support throughout my career journey. To God be the glory.

Dedication

This thesis is dedicated to the memory of my late mother, Mrs. Caroline Nnadili.

Biographical Note

Christopher Dozie Nnadili was born in Nigeria. After completing his primary and secondary school education, he earned a Bachelor of Engineering degree with high honors in Mechanical Engineering in 2002 from the Federal University of Technology Owerri, Nigeria. Between 2002 and 2003, he held a Project Engineer position at Channel Oil & Petroleum Limited.

In 2004, Christopher Nnadili enrolled in the Mechanical Engineering graduate program at the University of Missouri Rolla where he graduated with a Master of Science degree in 2005. From 2006 to 2007, he worked in the Centrilift Division of Baker Hughes as a Senior Associate Engineer.

Christopher Nnadili enrolled in the Supply Chain Management & Logistics program at the Massachusetts Institute of Technology in 2008 and graduated with a Master of Engineering in Logistics degree in 2009.

Table of Contents

List of Tables

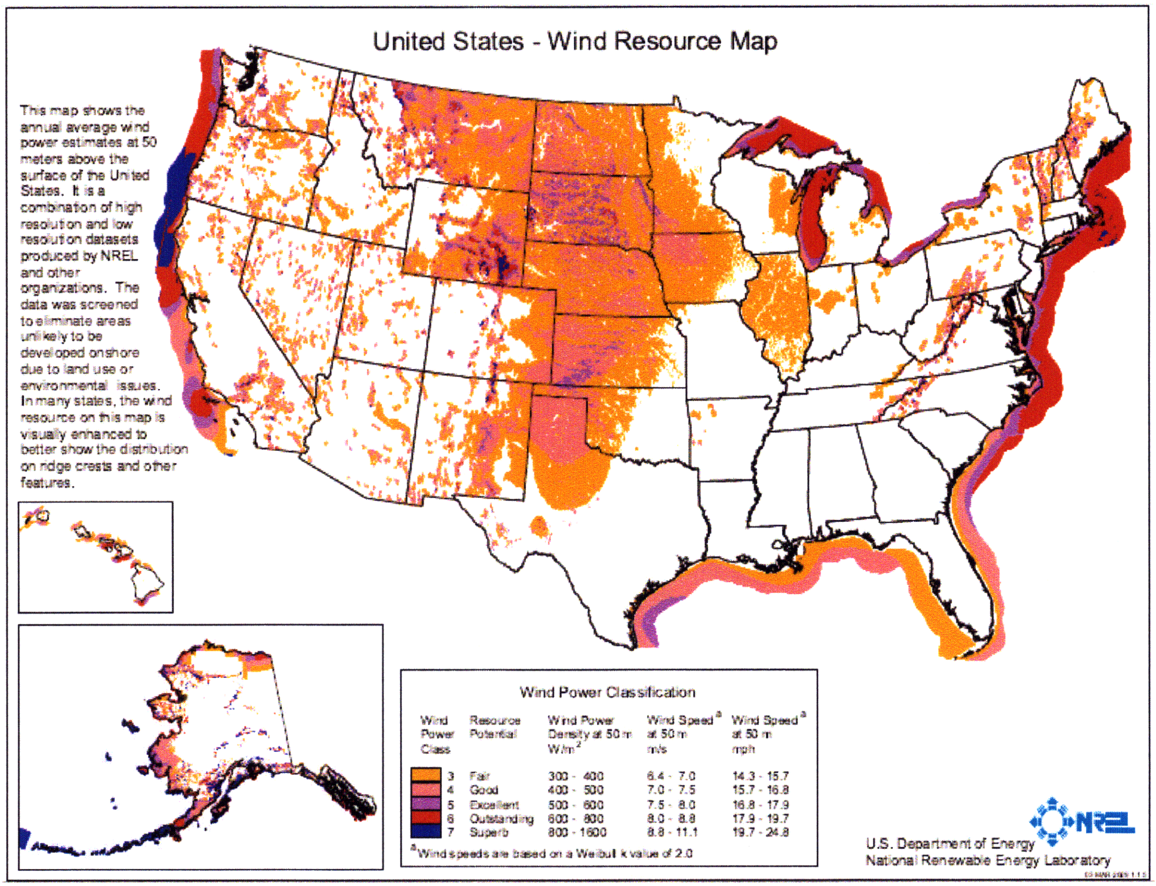
List of Figures

1 Introduction

According to the American Wind Energy Association (2009), wind energy installations in the United States generated 28,206 MW of installed capacity in the first quarter of 2009. As contained in the same report, new wind energy projects adding up to 2,836 MW were scheduled to be completed by the end of 2009. The total wind power generating capacity in operation in the United States was estimated to serve over 8 million homes and avoid the emissions of 52 million tons of carbon dioxide every year, equivalent to removing 8.8 million cars from the road. The renewed interest and consequent high growth rate of wind energy installations can be attributed to a number of factors. The main success factors include an existing 1.9 cent/kWh production energy tax credit for renewable energy sources and the decreasing cost of highly rated wind turbines as manufacturers continue to climb the learning curve. Despite this recent success of onshore installations in the United States, onshore wind farms still face numerous challenges mainly caused by location constraints, inaccessibility to high load centers, and electricity grid capacity.

Locating wind farms offshore has potential to overcome some of these challenges. Offshore wind farms will neither ruin the view nor make noise. Also, offshore wind farms can utilize larger turbines with more rated power production as they are not constrained to road and crane limits as is the case with onshore wind turbine installations. Perhaps more important is the proximity of offshore wind farms to high value load centers and less heavily loaded transmission lines close to the North Eastern coast of the United States. A wind resource map of the United States compiled by the National

Renewable Energy Laboratory in Figure 1 shows a high average annual wind power estimate off the coast of New England.



This map shows the annual average wind power estimates at 50 meters above the surface of the United States. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

Wind Power Classification

	Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
🟧	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
🟥	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
🟪	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
🟥	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
🟦	7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Figure 1 United States- Wind Resource Map
Source: National Renewable Energy Laboratory- www.nrel.gov

Figure 1 above illustrates that the red region located off the coast of New England has outstanding wind power characteristics (Class 6) which is able to utilize wind speeds of between 8.0 to 8.8 m/s to generate wind power density ranging from 600 to 800 W/m^2.

Over the years, an effort to capture this enormous offshore wind power as illustrated in Figure 1 led to the development of traditional offshore wind farms in many parts of Europe. Traditional offshore wind farms comprise of bottom mounted wind turbines utilizing either a monopile or gravity foundation. These traditional offshore wind farms with wind turbine support structure buried into the ocean bed in water depths between 5 m and 18 m have operated successfully in Europe for many years. In the United States, several traditional offshore wind farm projects which are currently in the approval phase have been delayed for several years because of resistance from residents close to the coastline.

In order to appease the concerns of coastline residents and generate wind energy from an offshore environment many miles off the coast, and in locations with water depths greater than 30 m, floating offshore wind farms have become necessary. The existing support structures for traditional wind farms are not technologically feasible in water depths exceeding 30 m thereby requiring a different support structure for wind turbines in deep waters. In order to harvest electricity from the high wind speeds in an offshore location, floating structures adapted from oilrigs are used to support the wind turbines.

This floating structure provides buoyancy to support the weight of the turbine and to restrict pitch, roll and heave motions to within tolerable limits. Some of the structures currently being developed for floating offshore wind turbines are spar buoys with mooring drag embedment anchors, tension leg platforms with suction pile anchors, and concrete tension leg platforms with a gravity base anchor. Figure 2 below shows the expected development path of offshore wind turbines similar to the path undergone by offshore oilrigs in the past 50 years.

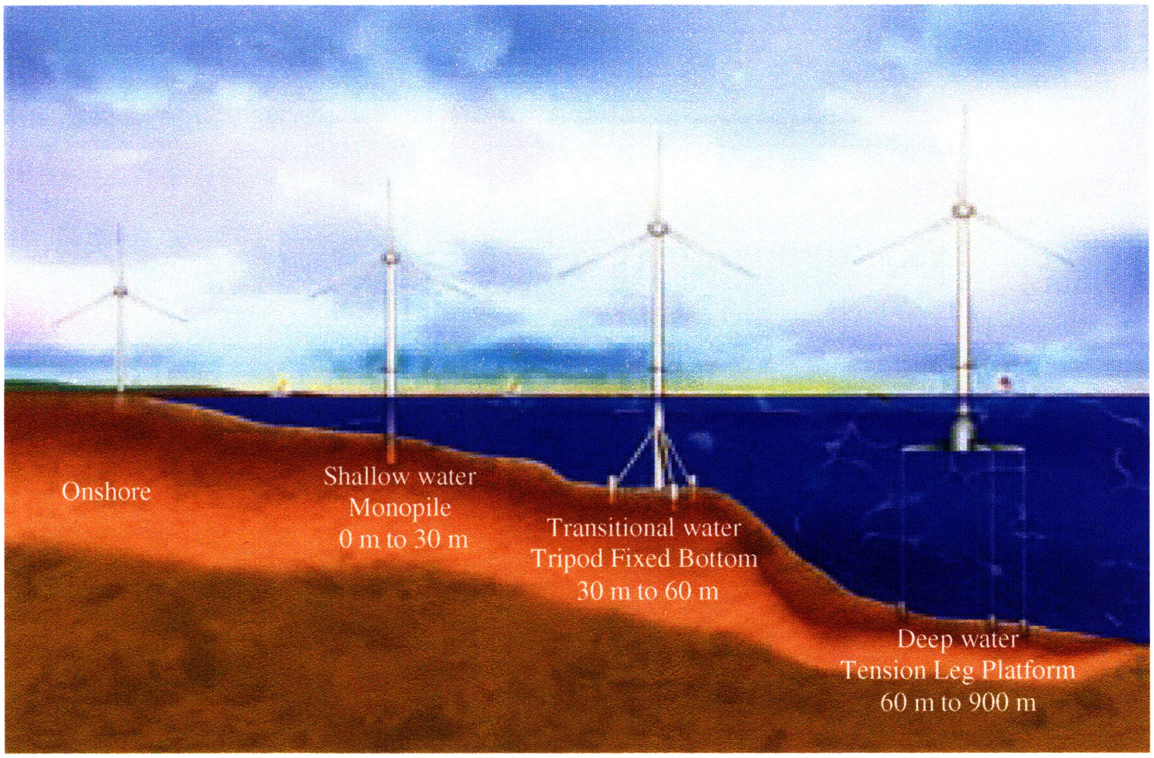


Figure 2 Development stages of Offshore Wind Turbines
Source: Musial W. Butterfield S., Ram B. (2006).

Floating offshore wind farms utilize larger wind turbines to generate more electricity, as there is no restriction to the size of the wind turbines installed in an offshore location because they do not face the same restrictions guiding onshore roadway or crane limits. The revenue stream from these larger machines with more electricity generating capacity is expected to offset the high cost of their offshore installation. At the time of this writing, many manufacturers have recently launched a 5 MW wind turbine specifically for offshore installations. There are development plans across the wind energy industry to build offshore wind turbines with power ratings of between 8 MW and 10 MW. Figure 3 below shows a picture of an offshore installation of a wind turbine.

Figure 3 Offshore Wind Turbine Installation
Source: GE 3.6 MW Arklow Project Installation. www.mammoetvanoord.com

1.1 Background of Floating Offshore Wind Farms

As reported by a study conducted by Manwell, Rogers, McGowan and Bailey (2002), offshore wind speeds off the New England coast ranged from 7.0 m/s to 8.4m/s at a machine hub height of 60 m above water level. Because water depths are higher in an offshore environment, a floating offshore platform is necessary to harvest electricity from a wind farm in these locations. It is therefore imperative to understand the effect of distance from shore on revenue from electricity sales for a floating offshore wind farm given the huge capital investment in both installation costs of wind turbines and operation and maintenance expenses that would be incurred.

Of particular interest to many wind energy proponents is an examination of the scalability of a floating offshore wind farm. To this end, the marginal impact of an additional mile on revenue from electricity sales for a floating offshore wind farm is pertinent. It is important to understand the tradeoffs between the revenue from electricity sales from a wind farm closer to shore to another one father away from shore given the increase in installation and operation & maintenance costs.

Higher offshore wind speeds are known to be steadier thereby reducing turbulence in wind turbines which in turn decreases failure rates for offshore wind turbine components. However because of the complexity and capital intensive nature of the operations and maintenance requirements of a floating offshore wind farm, offshore wind turbines are built to be robust in order to prevent frequent failures. In the event of a failure, it would be conducive for a wind farm operator to have replacement parts for a failed wind turbine component in on-hand inventory to repair the faulty wind turbine and restore electricity generation capacity in a timely manner. Choosing an appropriate maintenance strategy is therefore important in optimizing electricity generation from a floating offshore wind farm.

1.2 Thesis Objective and Scope

This thesis analyzes a hypothetical study of a 500 MW floating offshore wind farm which would utilize 100 units of 5 MW wind turbines located off the coast of New England.

First, wind speed data from 10 wind measurement stations with varying distances from the New England coastline was obtained from the National Data Buoy Center for the period 2006 to 2008 and analyzed to obtain average monthly wind speeds. Using this data, average monthly wind speeds were transposed using the power curve for a Repower 5M wind turbine to obtain electricity generated and hence revenue from electricity sold. Estimates of installation costs of wind turbines and the increasing cost of operating and maintaining the wind farm at varying distances from shore was obtained from published literature.

Second, marginal analysis was done to determine the impact of an additional wind turbine on electricity generated from the floating offshore wind farm.

Finally because of unavailability of offshore wind turbine data, failure rates of a GE onshore wind turbine was used to determine demand for offshore wind turbine components after necessary adjustments was made for reduced turbulence as contained in published literature. Suggestions for an appropriate inventory policy was examined and presented.

This thesis will serve as a blueprint for prospective operators of a floating offshore wind farm in demand planning and tackling logistical challenges for electricity generation.

2 Literature Review

Musial, Butterfield and Ram (2006) provide an overview of the offshore wind energy industry in the United States and in particular, the potential for floating offshore wind turbine applications. They submit that critical to the development of floating offshore wind farms would be synergies between the burgeoning offshore wind energy industry and more established knowledge from the offshore oil and gas industry. In order to achieve favorable economics and reduce full system life cycle costs, expertise from the oil and gas industry in functional areas such as performing site assessments, laying and maintaining sub marine cables and geotechnical engineering will be necessary. From their preliminary analysis reported by the US Department of Energy, offshore wind in the United States has a potential to generate 50 GW of electricity in 20 years, representing 5% of the nation's electricity generating capability. This installed capacity, according to Musial, Butterfield and Ram (2006), represents approximately $100 billion in capital investment and a potential to double capacity in another 10 years to 100 GW.

In an earlier study by Musial, Butterfield and Boone (2004), a cost comparison of the Dutch tri-floater developed by ECN was compared to the tension leg platform concept of the National Renewable Energy Laboratory. Costs estimates suggest that the single 5 MW unit production cost for a Dutch tri-floater is $7.1 million while the tension leg platform costs $6.5 million. By outsourcing manufacturing to Asia as explained in Dutch report published in 2002, a 20% to 40% reduction in cost can be obtained reducing the cost of the tri-floater to $4.26 million. Similarly, a more conservative review of cost estimates by the National Renewable Energy Laboratory indicated that a tension leg platform can achieve a reduction in cost to $2.88 million. These foundation costs were found to be within bounds required to bring the cost of energy down to the US Department of Energy set target of $0.05/kWh for large scale development of floating offshore wind farms.

Manwell, Rogers, McGowan and Bailey (2002) assessed the offshore wind resource in southern New England by utilizing hourly wind and direction data from the National Data Buoy Center (NDBC). Half of the 12 data measuring stations used for this study where located on land while the other half were floating buoys in waters of 19-88m depth located 12-170 nautical miles from shore. Because anemometers used to collect wind speed data from these floating buoys were located 5m above sea level, wind speed data taken from them were extrapolated to typical wind tower hub heights of 60m. Similarly, anemometers used for collecting wind data on land were placed 13.8-49.1m high and had to be modified accordingly. By using a nominal roughness height of 0.2mm for open water and 0.5mm for sites on land, log law was applied to extrapolate wind speed data to typical hub heights of 60m.

In order to measure wind speeds at a test site, Manwell, Rogers, McGowan and Bailey (2002) utilized the Measure Correlate and Predict (MCP) method to forecast wind speeds by collecting wind speeds and direction time series data from a reference site within the vicinity of the test site. The mesoscale weather modeling system (MesoMap) was also used to collect historical atmospheric data at multiple levels to determine wind characteristics around the border of a set boundary.

Farrugia studied the use of the power law relationship (1/7th power law) to extrapolate wind speed data captured by anemometers placed at 25m from the ground level to actual wind speeds at wind turbine machine hub heights which stand above 80m. Using the power law relation, wind shear exponent of 0.14 (1/7) was found to be sufficient for extrapolation in near neutral (adiabatic) conditions up to 100m. Using anemometers placed at 10m and 25m above ground level in Swatar located on a high ground in Malta's South West, Farrugia observed seasonal variations is wind shear component. Wind shear exponent varied from the hot summer months to the cold winter months from 0.29 to 0.45 with an annual average of 0.36. Similarly, Farrugia found a diurnal variation of the wind shear exponent during the day. Wind shear exponent increased at night and reduced during the day.

van Bussel and Zaaijer (2001) identified reliability, availability, maintainability, serviceability and accessibility as critical factors affecting the operation of wind turbine components in an offshore wind farm. Apart from the difficulty and huge expense of installing wind turbines in an offshore environment, access to them for maintenance largely depends of weather conditions (wind and waves). Also lifting actions which are performed relatively easy on land require special and sometimes scarce equipment to perform in an offshore environment. The schematic diagram in Figure 4 below illustrates the principal drivers of operations and maintenance of an offshore wind farm. Because site accessibility is always below 100% in an offshore environment, it is important to decrease failure frequency in offshore wind components by selecting the most reliable implementation, adding redundancy to sub-components and using MIL-specs components. Because offshore work is between 5 to 10 times more expensive than work on land and given the bi-annual service requirement of operating wind farms and repair work needed when failure occurs, it is important for an offshore wind farm operator to address the cranage problem by purchasing one. This bi-annual service which takes about 40 to 80 man hours is complemented by a more intensive service action taken every 5 years to overhaul major components and replace worn out parts. Given this high service requirements, 4 design models for future offshore wind farms were evaluated which includes reduction in the number of wind turbine components to a minimum, a modular design approach, use of integrated components and an integral exchange model.

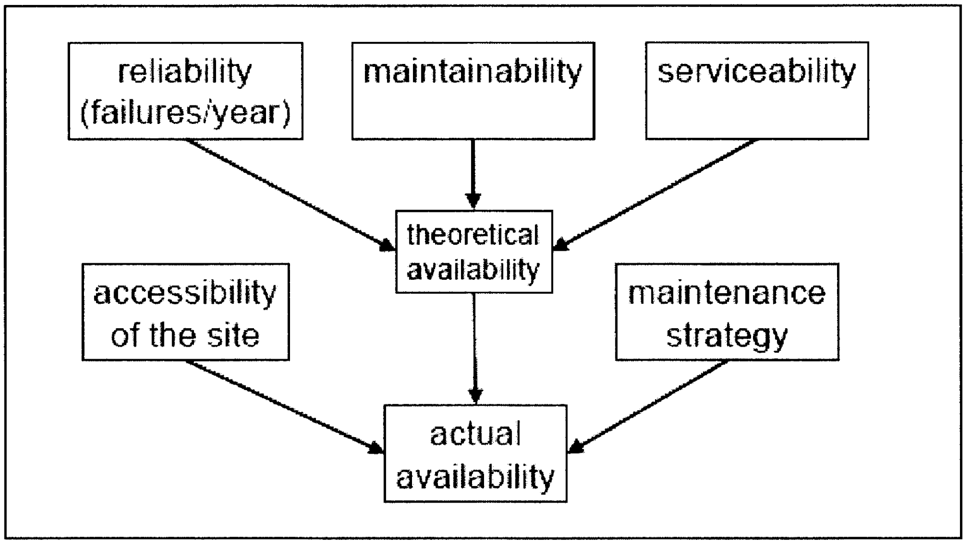


Figure 4 Schematic of Operations & Maintenance of offshore wind farms
Source: Van Bussel G.J.W., Zaaijer M.B.(2001).

Rademakers, Braam, Obdam, Frahbose and Kruse (2008) developed an ECN software tool for estimating the annual operations and maintenance cost of an offshore wind farm using input parameters such as the failure behavior of turbine components in terms of failure frequencies and associated repair actions, access vessels and hoisting equipment as well as wind and wave climate at the offshore location. After identifying calendar based maintenance, unplanned corrective maintenance and condition based maintenance as possible maintenance strategies for offshore wind farms, an extensive list of input parameters and detailed description of the operations and maintenance strategy was used to obtain output in terms of cost, downtime and revenue losses. The MS- Excel model developed incorporated the add-in module @Risk to perform uncertainty analysis to determine which random input parameters influence the uncertainty of the software tool results. This software tool was validated by GL Wind which certified that the inherent models, computation codes and influence of wind and wave data on the software results were plausible. The schematic diagram in Figure 5 below represents an ECN operation and maintenance tool for determining costs and downtime in an offshore wind farm.

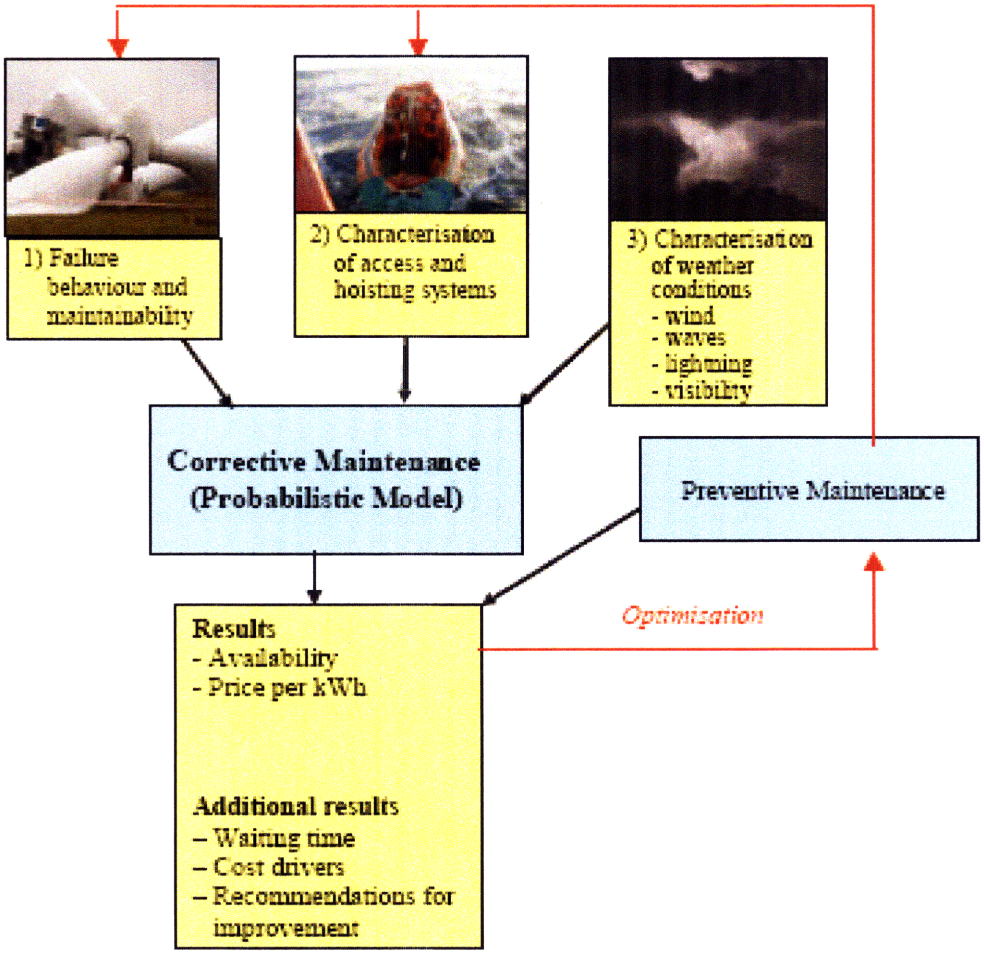


Figure 5 Schematic diagram of ECN Tool for an offshore wind farm
Source: Rademakers L.W.M.M., Braam H., Obdam T.S., Frohbose P., Kruse N. (2008).

3 Wind Farm Location

It has been established by many published literature that wind speeds are higher in an offshore environment. However there has not been an effort to determine the distance from shore at which it would be economical viable to site a floating offshore wind farm. In order to operate a profitable floating offshore wind farm, an economical approach to finding an appropriate distance from shore is necessary in harvesting electricity generated from wind farms.

3.1 Determination of Offshore Wind Speeds

To determine offshore wind speeds, data was downloaded from the website of the National Data Buoy Center which hosts the most comprehensive wind measurement data in the United States. Annual wind measurement data taken at intervals between 10 minutes to 60 minutes which contains metrics such as wind direction, wind speed, wind gust, wave height, dominant wave period, average period, atmospheric pressure, pressure tendency, air temperature, water temperature, dew point and wind chill, was downloaded to a spreadsheet program and analyzed. Figure 6 below shows buoy locations in the coastal areas of the North Eastern region of the United States. Some of the 10 wind data measuring stations shown in Figure 6 were either located on islands or directly on the coastline while the others are floating buoys out in the water. The stations are located between 3 and 55 miles from the closest shore with anemometer heights at 4 m to 5m from sea level. Wind measurement data dating back from 1975 to 2008 were obtained from these stations. However, in some recently installed stations datasets for only six years (2003 to 2008) were available.

Figure 6 Buoy locations in North Eastern region of the United States
Source: National Data Buoy Association. http://www.ndbc.noaa.gov/obs.shtml

The longitudinal and latitudinal locations of the data measuring stations were collected and actual distance from the nearest coastline was obtained by using the measuring scale function on Google Earth software. The yellow pinpoints in Figure 7 show some of the location of the stations utilized for this analysis.

Wind measurement data taken from 2006 to 2008 from 10 stations located at various distances off the coast of New England was culled from the website of the National Data Buoy Center and cleaned up to remove erroneous wind speed data measuring 0 m/s and 99m/s. The distance of the measuring stations from shore was read off using the measuring scale function on Google Earth. Using MS-Access database, historical average monthly wind speeds for each of the stations was computed and the results were exported to a MS-Excel for charting.

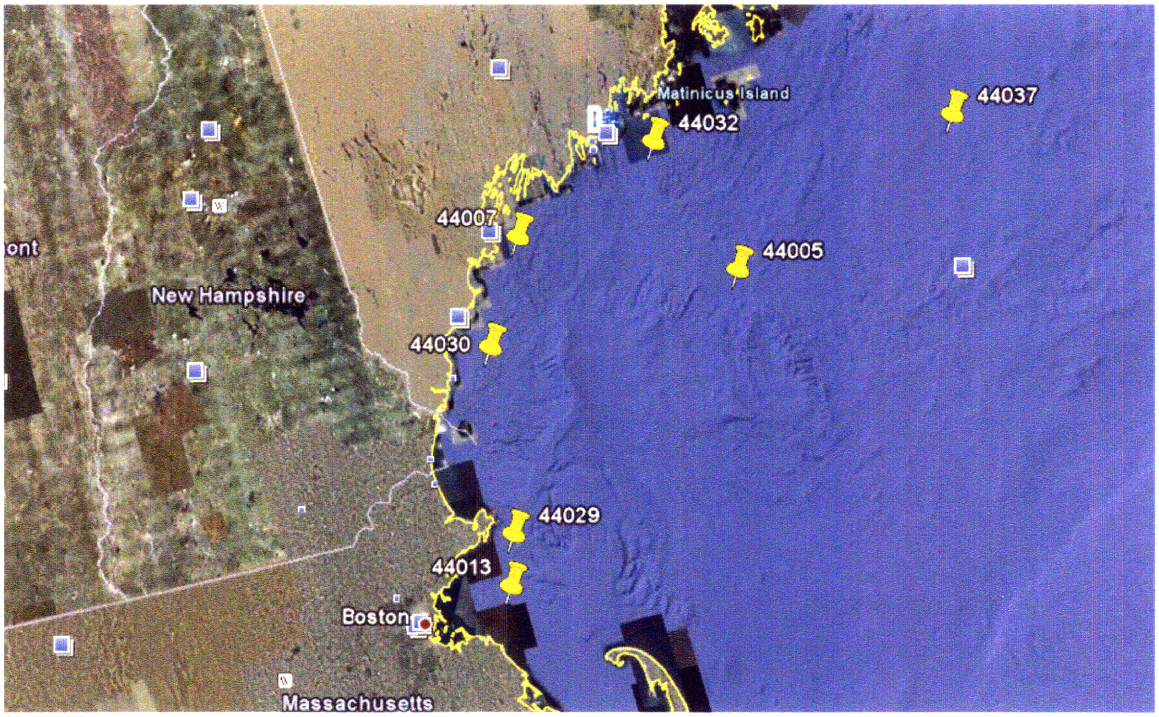


Figure 7 Google Map software of wind measurement stations
Source: Google Earth

3.2 Determination of Power Output from Wind Speeds

As reported by Farrugia (2003) the power law relationship was used to transpose the wind speed measurements at anemometer heights of 4 m and 5 m to a wind turbine hub height of 80 m. In the relationship,

$\frac{\bar{v}(h)}{\bar{v}(h_r)} = \left(\frac{h}{h_r}\right)^{\propto}$, where

h = wind turbine hub height

h_r = anemometer height,

v(h) = speed at hub height

v(h_r) = speed at anemometer height

α = wind shear exponent

Farrugia (2003) found that wind shear exponent value of approximately 1/7 (0.14) describes atmospheric wind profiles over the range up to the first 100 m sufficiently well during near-neutral adiabatic conditions. However, previous studies have used power law exponents as large as 0.50 for heights ranging between 30m and 150m.

Bailey (1981) observed that wind shear exponent depended on atmospheric stability, wind speed, roughness length and the height interval. Because significant errors would arise if a single exponent were used, a recommendation of an average component for each site was made. In this analysis, a wind shear exponent of 0.2 was chosen to keep estimates of actual wind speeds conservative.

A power curve table from REpower 5 MW wind turbine was used to estimate power output of the modified wind speeds from the transposition. This machine is calibrated to operate with a rotor diameter of 126 m and air density of 1.225 kg/m^3. It operates with a cut in wind speed of 3.5 m/s and cut out wind speed of 30 m/s in an offshore environment. The table below (Table 1) obtained from Repower 5M power curve shows wind speeds and estimated power output from this wind turbine under 6% to 12% turbulence intensity, vertical wind shear coefficient less than 0.2, maximum air density less than 1.13 kg/m^3 and temperature ranges less than 35C. Using the wind speed and power data in Table 1, a power equation between wind speed and power output was used as shown in Figure 8 to obtain annual output from each of the wind measurement stations.

Table 1 Power Curve Output of REpower 5M

Wind Speed (m/s)	Power Output (kW)
3.5	53
4.0	126
5.0	352
6.0	648
7.0	1081
8.0	1638
9.0	2335
10.0	3170
11.0	4017
12.0	4755
13.0	5000
14.0 - 30.0	5000

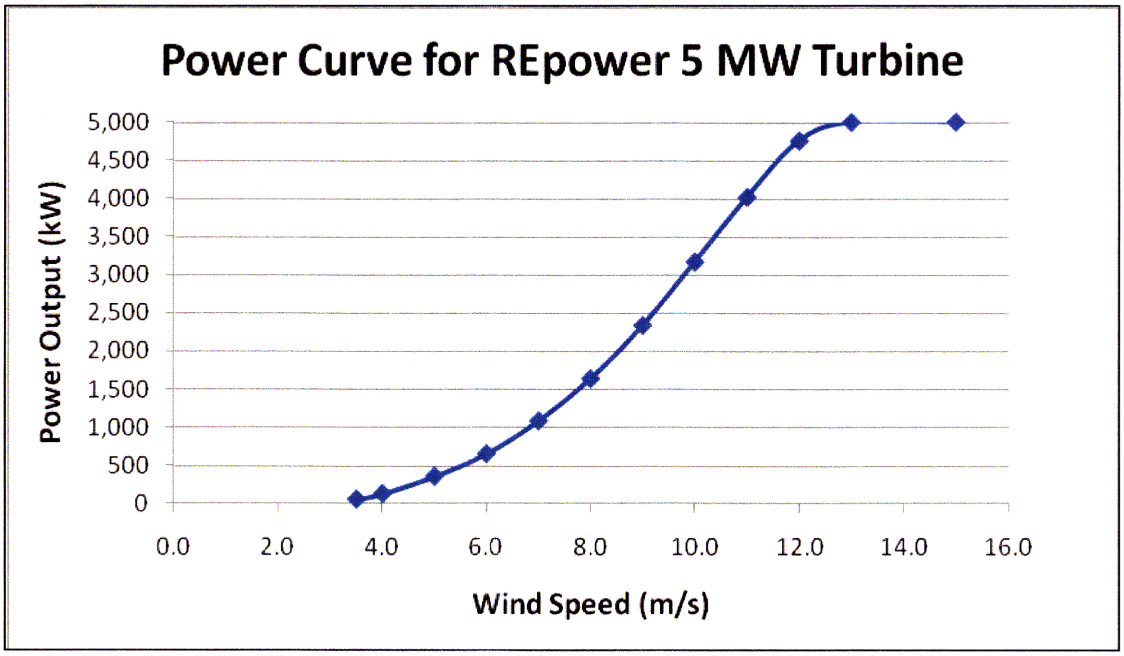


Figure 8 Power Curve Output from Repower 5 MW wind turbine

Actual power output was estimated by using a conservative wind energy industry capacity factor of 40% of rated power from the 10 measuring stations. Because wind speed is not constant, a wind farm's annual energy production is never as much as the sum of the generator nameplate ratings multiplied by the total hours in a year. The ratio of actual productivity in a year to this theoretical maximum is called the capacity factor. The tables below (Tables 2, 3 and 4) show historical wind speed data for 2006 – 2008.

Table 2 2006 Summary Wind Speed Data and Power Output Estimate

Measuring Station	Distance from Shore	Annual Average Speed (m/s)	Anemometer Height (m)	Modified Average Wind Speed (m/s)	Power Output (kWH)
44007	3.51	5.49	5	9.56	7,912,767
44029	6.19	5.73	4	10.43	10,423,244
44030	7.94	5.54	4	10.09	9,394,498
44013	9.23	5.98	5	10.40	10,340,326
44032	11.39	5.67	4	10.32	10,077,034
44025	25.12	6.43	5	11.19	13,021,667
44008	36.68	6.38	5	11.11	12,719,567
44018	43.08	6.47	5	11.26	13,297,318
44005	50.13	6.72	5	11.70	14,986,387
44037	55.24	7.81	4	14.21	17,520,000

Table 3 2007 Summary Wind Speed Data and Power Output Estimate

Measuring Station	Distance from Shore	Annual Average Speed (m/s)	Anemometer Height (m)	Modified Average Wind Speed (m/s)	Power Output (kWH)
44007	3.51	5.59	5	9.19	6,978,341
44029	6.19	5.95	4	10.23	9,815,728
44030	7.94	6.26	4	10.76	11,513,098
44013	9.23	6.08	5	10.00	9,116,986
44032	11.39	6.40	4	11.00	12,347,209
44025	25.12	8.42	5	13.85	17,520,000
44008	36.68	6.03	5	9.92	8,895,506
44018	43.08	6.71	5	11.03	12,446,923
44005	50.13	6.52	5	10.73	11,413,764
44037	55.24	5.72	4	9.84	8,654,088

Table 4 2008 Summary Wind Speed Data and Power Output Estimate

Measuring Station	Distance from Shore	Annual Average Speed (m/s)	Anemometer Height (m)	Modified Average Wind Speed (m/s)	Power Output (kWH)
44007	3.51	5.44	5	8.95	6,413,245
44029	6.19	5.54	4	9.54	7,852,813
44030	7.94	5.51	4	9.49	7,713,632
44013	9.23	5.90	5	9.70	8,275,547
44032	11.39	5.71	4	9.82	8,608,746
44025	25.12	6.64	5	10.92	12,061,112
44008	36.68	6.73	5	11.07	12,576,893
44018	43.08	6.22	5	10.23	9,815,795
44005	50.13	6.60	5	10.86	11,861,219
44037	55.24	6.73	4	11.58	14,535,983

The accompanying Figure 9 charts power output with distance from shore for the 10 stations from 2006 to 2008.

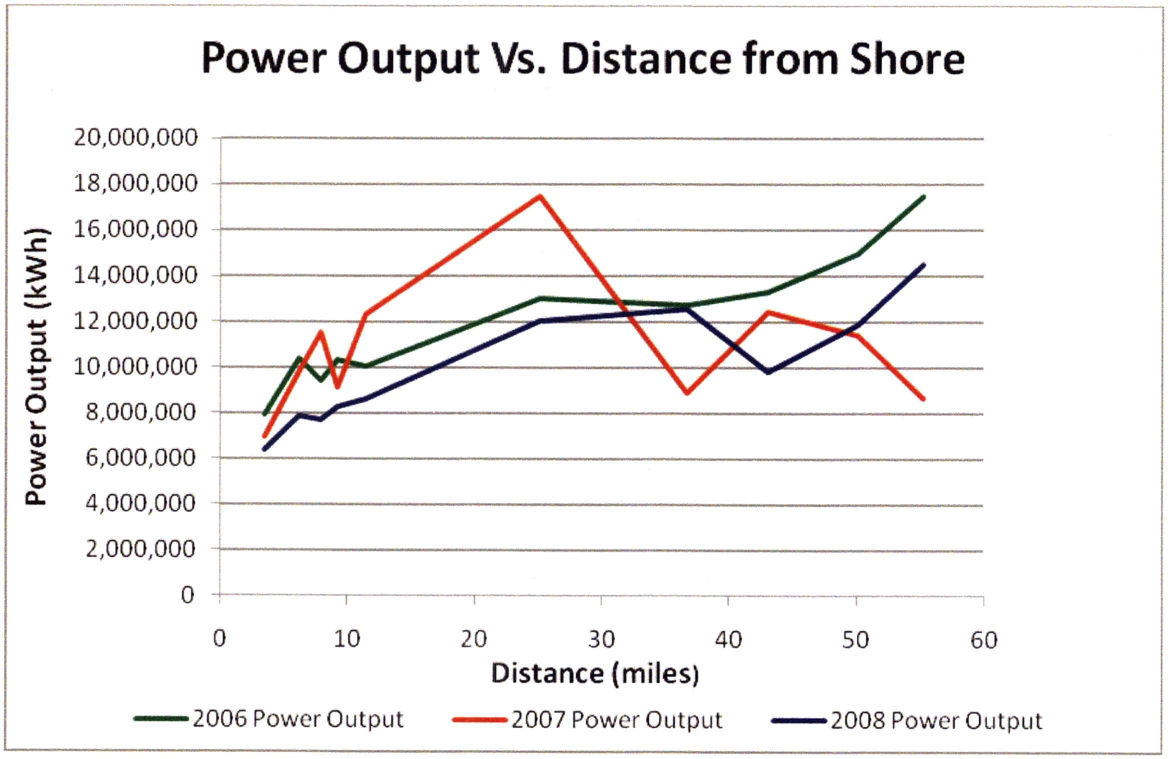


Figure 9 Historical Power output vs. Distance Chart

3.3 Location and Marginal Effect of Distance from Shore

As reported by Musial, Butterfield and Ram (2006), the cost breakdown of a floating offshore wind farm can be broken down into 6 cost segments including turbine, support structure, grid connection, management, operation and maintenance and decommissioning costs as illustrated in Figure 10. From the cost breakdown it can be deduced that favorable economics in wind turbines utilized for offshore applications depends on the total system life cycle cost and less on the turbine cost. From Figure 10 below, the electrical and grid infrastructure, foundations and support structures, offshore construction, and operations and maintenance now represent the major fraction of the total cost of an offshore wind farm.

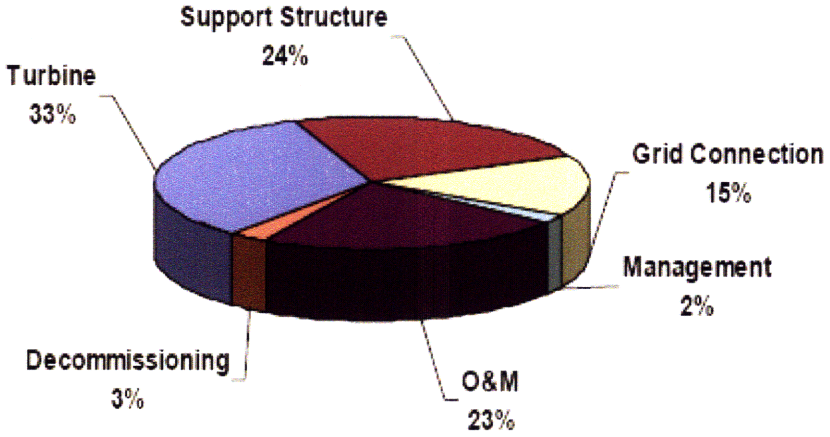


Figure 10 Cost Breakdown of Floating Offshore Wind Farm
Source: Musial W., Butterfield S., Ram B. (2006). Energy from Offshore Wind

The costs considered in this analysis are operations & maintenance cost, cable cost, levelized production cost (includes installation, wind turbine and transmission cost), and support structure cost (in this case: a tension leg platform).

The annual operations and maintenance cost for a floating offshore wind farm was estimated to be 30% of the revenue generated from electricity sales, as have been used in many previous studies including van Bussel and Zaaijer (2001).

The transmission cable chosen for this study are high voltage direct current (HVDC) submarine cable. According to Ackerman (2005), a power transmission loss for HVDC cables show a very limited correlation with the length of the cable but depend on the efficiency of the converter stations. Ackerman (2005) estimated transmission losses of the order of 2 – 3% for HVDC cables which was accounted for in this analysis.

Because of unavailability of water depth data at each of the 10 measuring stations, a uniform water depth of 100 m was assumed for all stations. Using a rule of thumb cost of $1 million per mile of cable, cable cost was amortized over the 50 year life span of HVDC type submarine cables utilized for offshore environments in deep waters.

The levelized production cost is an aggregate estimate of the cost of generating electricity from a floating offshore wind farm. It includes the cost of installed equipment such as wind turbine, converter stations and the cost of connecting to the electricity grid. This cost was estimated to amount to 6 cents/kWh by the American Wind Energy Association.

The cost of the tension leg platform support structure estimated at $2.88 million by the National renewable Energy Laboratory was reported by Musial Butterfield and Boone (2004). This cost assumes a $1/lb of steel and could be as much as $6.5m for $2/lb of steel. A cost of $2.88 million for each of the 100 floating support structures was amortized over a 50 year life span.

The prevailing market price for electricity in the North Eastern region of the United States at the time of this writing averaged 10 cents/kWh. This price was used to determine revenues and profit from electricity sales generated by the hypothetical wind farm comprising 100 wind turbines. This number of wind turbines was chosen because a study conducted by Junginger, Faaij and Turkenburg (2004) concluded that wind farm operators could can achieved a 30% cost reduction off the list price of wind turbines by ordering up to 100 turbines.

Figure 11 below aggregates the costs of a floating offshore wind farm described above.

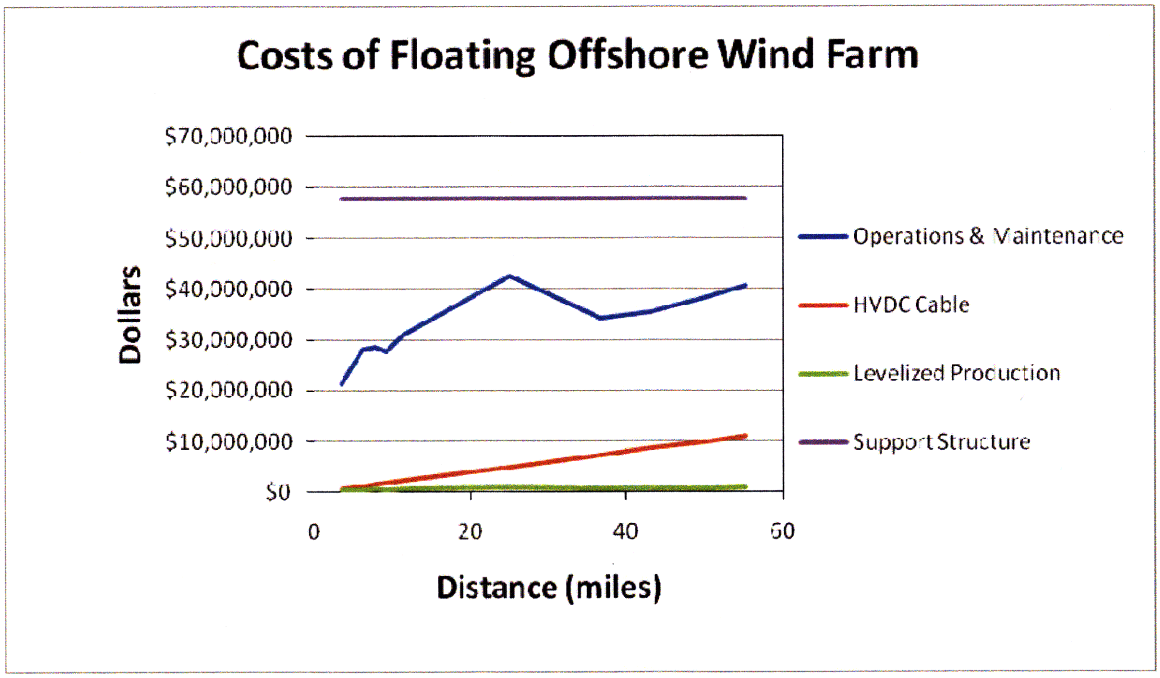


Figure 11 Costs for Floating Offshore Wind Farm

As discussed earlier the support structure cost and the levelized production cost are constant because the former was amortized for the 50 year life span of the wind farm while the latter was is constant for each kWh of electricity generated. On the other hand, the cost of the HVDC cable and the operation & maintenance costs increased with distance from shore of the floating offshore wind farm.

The table below (Table 5) shows a sample of calculations done to determine revenues and costs of a 100 turbine hypothetical floating offshore wind farm with distance from shore in 2008.

Table 5 Revenue, Cost and Profit for Measuring Stations

Measuring Station	Distance from Shore (miles)	Revenue	Total Cost	Profit
44007	3.51	$79,127,670	$82,521,474	-$3,393,804
44029	6.19	$104,232,435	$90,739,591	$13,492,844
44030	7.94	$93,944,980	$87,941,669	$6,003,312
44013	9.23	$103,403,263	$91,093,932	$12,309,332
44032	11.39	$100,770,338	$90,720,304	$10,050,034
44025	25.12	$130,216,666	$102,477,182	$27,739,484
44008	36.68	$127,195,671	$103,865,011	$23,330,659
44018	43.08	$132,973,183	$106,913,071	$26,060,112
44005	50.13	$149,863,869	$113,491,776	$36,372,093
44037	55.24	$175,200,000	$122,266,744	$52,933,256

Because of unavailability of data, it is not certain that wind speeds will continue to increase with distance from shore. More importantly, changing weather patterns does not suggest that average wind speeds at certain distances from shore are constant year to year. Under the assumption that wind speed remain constant after 55.24 miles from shore, the computed average historical revenue and cost for all 10 measuring stations was used find the distance from shore at which a floating offshore wind farm would operate unprofitably. Figure 12 shows the result of extrapolating the total costs to the revenue stream obtained under this assumption.

From the Figure 12 below, it can be deduced that if wind speeds were to remain constant after 55.24 miles, the cost of operating a wind farm would exceed revenues from electricity generation at 145 miles from the closest shore.

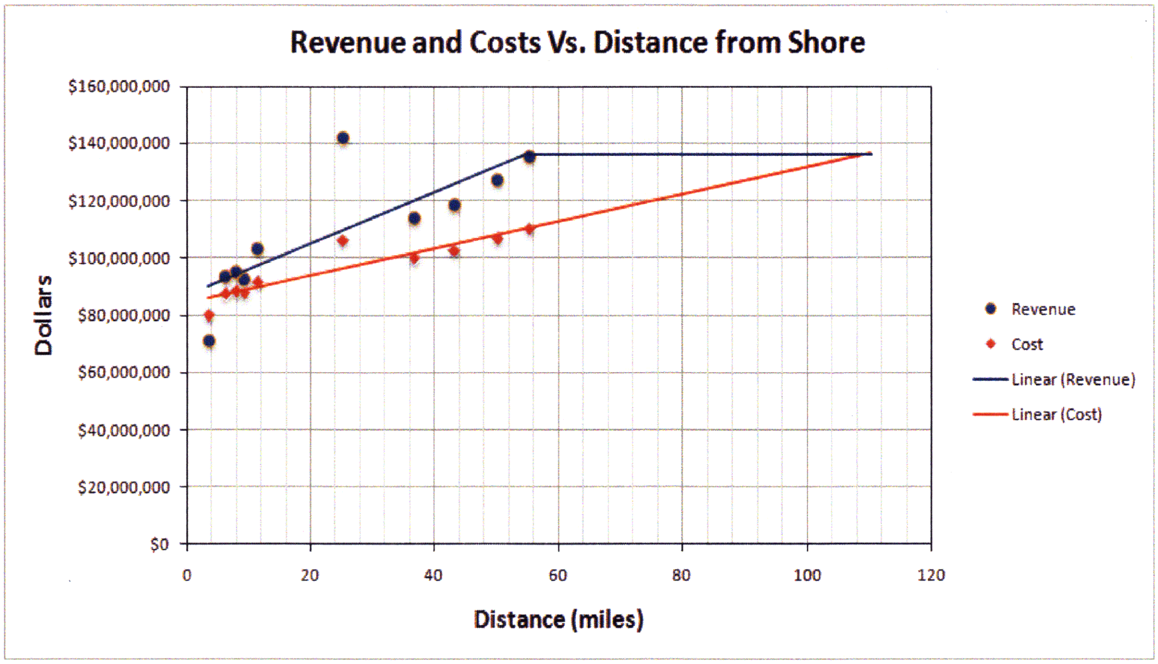


Figure 12 Aggregate Historical Revenue and Cost vs. Distance from shore

From Figure 12 above, under the assumption that wind speed remains constant after a 55.24 mile distance from the closest shore, the revenue from electricity generated will be $138 million. As the cost of generating electricity from the floating offshore wind farm increases with distance from shore, it would become unprofitable to operate a wind farm after 145 miles. Changing weather patterns show that locating the wind farm farther from shore may in some years negatively impact profitability. However, it does not suggest that offshore wind farms are unprofitable. Taking together, one can surmise that there might be an optimal distance from shore for a floating offshore wind farm as it does not seem reasonable to locate one in the middle of the Atlantic Ocean. Based on the data available, it may be impossible to forecast future weather patterns in order to determine with reasonable accuracy where the optimal distance lies.

4 Inventory Policy for Wind Turbine Components

The complexity of operating and maintaining a floating offshore wind farm has created a direct link between its inventory policy and the farms maintenance schedule. Because floating offshore wind farms are not accessible in severe weather conditions, planning an appropriate inventory policy is challenging. The high cost of transporting a self propelling jack-up rig required for maintaining wind turbine components such as the blades and tower adds to the cost of a wind farms inventory policy. More so planning the logistics of the self propelling jack up rig for trips to an offshore wind farm in inclement weather is complicated.

van Bussel and Zaaijer (2001) studied the failure rate of wind turbine components and summarized them in Table 6.

Table 6 Failure rates of offshore wind turbine components

Component	**Onshore failure frequency (failures/year)**	**Offshore failure frequency (failures/year)**
Shaft and Bearings	0.02	0.02
Brake	0.05	0.05
Generator	0.05	0.05
Parking Brake	0.05	0.05
Electrical Parts	0.14	0.1
Blade	0.16	0.11
Yaw System	0.23	0.15
Blade Tips	0.28	0.14
Pitch Mechanism	0.28	0.14
Gearbox	0.3	0.15
Inverter	0.32	0.16
Control	0.34	0.17
Total	**2.2**	**1.28**

Source: Van Bussel G.J.W., Zaaijer M.B.(2001).

From the table above it can be seen that offshore failure rates are significantly lower than onshore failure rates. Apart from the fact that manufacturer tend to build more robust wind turbines for offshore applications, high wind speeds in an offshore location results in a low turbulence on wind turbine components which reduces their failure rates.

4.1 Cost Analysis of Offshore Wind Turbine Inventory

Using failure rates data for offshore wind turbines provided by van Bussel and Zaaijer (2001), demand for a 100 unit wind farm was computed by simply multiplying the failure rates by 100. In order to calculate the safety stock, weekly failure rates were computed because lead times for wind turbine component orders were assumed to range from 2 and 4 weeks. A sensitivity analysis was necessary to examine the variation in these lead times to understand the impact on safety stock costs.

Assuming a Poisson distribution for these slow moving wind turbine components, the safety stock for each wind turbine component was back calculated by assuming service levels of above 95% and 99%. A periodic review policy is assumed because of the high cost and low number of wind turbine components required to be stocked. At each instance, when the level of wind turbine component inventory falls below the safety stock, new components will be ordered for replenishment.

The wind turbine component percentage costs were obtained from Burton, Sharpe, Jenkins and Bossanyi (2001). These percentages were multiplied by offshore wind turbine system cost of $7 million to obtain the individual wind turbine component costs. These costs were then multiplied by the safety stock to obtain inventory cost for the safety stock. Assuming a capital charge of 15%, inventory holding costs was also computed. Table 7 show a sample of the calculation described above for a 4 week lead time and 99% service level.

Table 7 Inventory Cost Analysis of 4 week Lead Time & 99% Service Level

Wind Turbine Components	Offshore Failure Rates (failures/year)	Wind Farm Annual Demand	Demand over Lead Time	Safety Stock	Percentage Costs	Component Costs	Inventory Costs	Inventory Holding Costs
Shaft and	0.02	2	0.15	2	4.2%	$294,000	$588,000	$88,200
Brake	0.05	5	0.38	2	1.7%	$119,000	$238,000	$35,700
Generator	0.05	5	0.38	2	7.5%	$525,000	$1,050,000	$157,500
Parking Brake	0.05	5	0.38	2	5.0%	$350,000	$700,000	$105,000
Electric Parts	0.10	10	0.77	3	21.0%	$1,470,000	$4,410,000	$661,500
Blade	0.11	11	0.85	4	18.0%	$1,260,000	$5,040,000	$756,000
Yaw System	0.15	15	1.15	4	4.2%	$294,000	$1,176,000	$176,400
Blade Tips	0.14	14	1.08	4	12.0%	$840,000	$3,360,000	$504,000
Pitch	0.14	14	1.08	4	4.0%	$280,000	$1,120,000	$168,000
Gearbox	0.15	15	1.15	4	12.5%	$875,000	$3,500,000	$525,000
Inverter	0.16	16	1.23	4	2.5%	$175,000	$700,000	$105,000
Control	0.17	17	1.31	5	7.4%	$518,000	$2,590,000	$388,500
Total	**1.28**	**128**					**$24,472,000**	**$3,670,800**

Inventory costs as shown in the table above describe the order cost of wind turbine components which include the cost of the components and their transportation costs. Inventory holding costs shown in the table include associated costs such as taxes and insurance, maintenance cost, obsolescence cost and opportunity cost of keeping wind turbine component inventory.

Table 8 show a summary of the results of a sensitivity analysis performed to determine the effect of varying lead times (2 and 4 weeks) and service levels (95% and 99%) on inventory holding costs.

Table 8 Sensitivity Analysis Summary for Inventory Holding Cost

Lead Time	**Service Level**	
	95%	**99%**
2	$1,906,800	$2,503,200
4	$2,692,200	$3,670,800

From the table above, the inventory holding cost is insignificant when compared to the total cost of running the floating offshore wind farm. In table 5 (Chapter 3), the cost of operating the wind farm will be about $100 million depending on its distance from shore. Moving from a 95% service level to a 99% service level will be at most $1 million which is only 1% of the total costs. Therefore the inventory policy should require high service levels.

4.2 Simulation of Weekly Wind Turbine Component Failure

From the wind turbine failure rate table given by van Bussel and Zaaijer (2001) in Table 6, a Monte Carlo simulation was generated for weekly wind turbine component failure. This was necessary to decide which maintenance strategy would be best for a floating offshore wind farm which will be discussed in the next section.

The following assumptions were made in generating the simulation. First, it is assumed that wind turbine component failures follow a Poisson process. Second, each component failure is independent of another component failure. For instance, a failure of a blade will not affect a generator. Third, the failure rate is not dependent on the number of failures. This is because each component on a specific wind turbine is not simulated; only component categories of the entire wind farm are simulated. This should be a valid assumption because the failure rates of each component are small.

By assuming that failure rates follow as a Poisson Process, the exponential distribution can be used to model the inter-arrival times between failures. The inter-arrival times of failures for each component are then generated by mapping random numbers to the inverse of the cumulative exponential distribution. Inter-arrival times are converted to an absolute time scale to obtain a simulation of weekly part failure, which is shown in Figure 13.

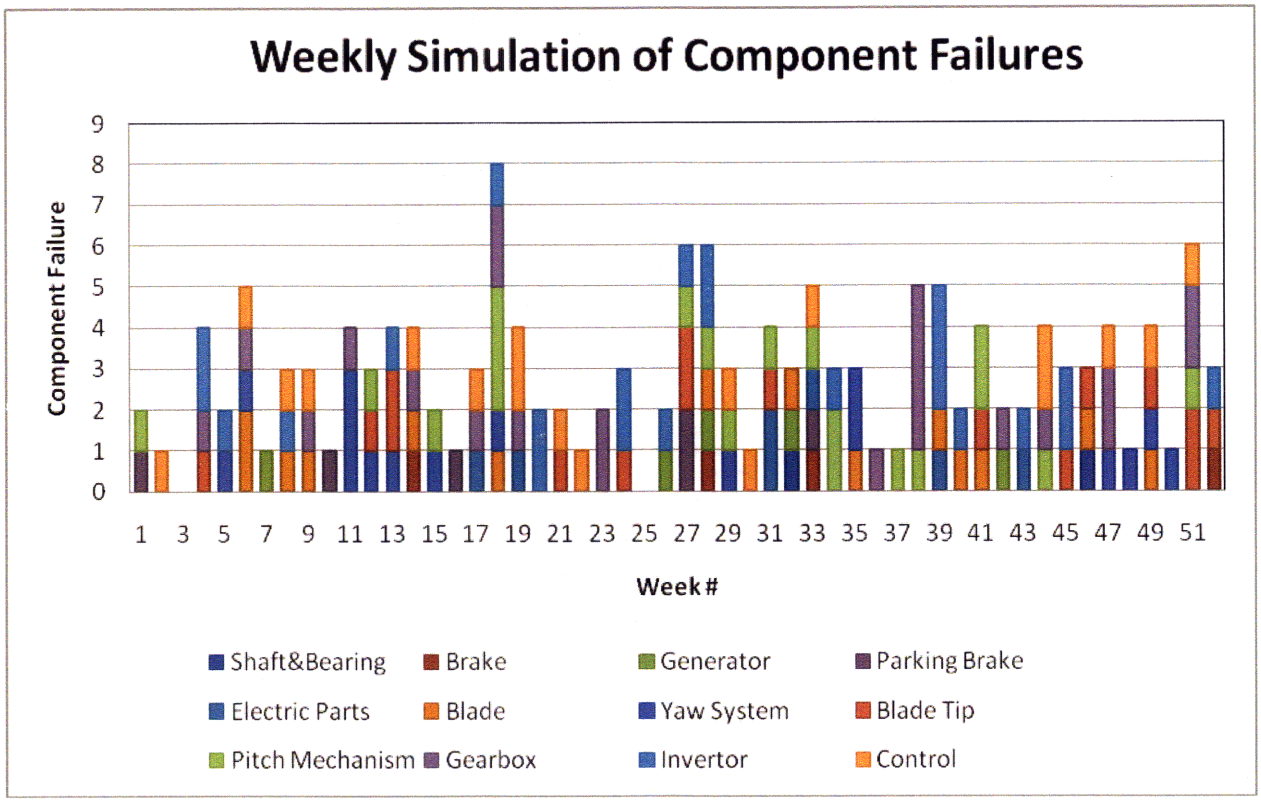


Figure 13 Weekly Simulation of Component Failure over 52 Weeks

Figure 13 shows simulation results for 52 weeks. As can be observed, there were component failures for every week except weeks 3 and 25. Week 18 had the highest number of component failures throughout the 52 week simulation. On average, there are 3.38 part failures per week.

To simulate the number of failure during the 50 year life span of a floating offshore wind farm, 2600 weeks of simulation was generate. Figure 15 show the histogram of the component failures of 2600 weeks of simulation.

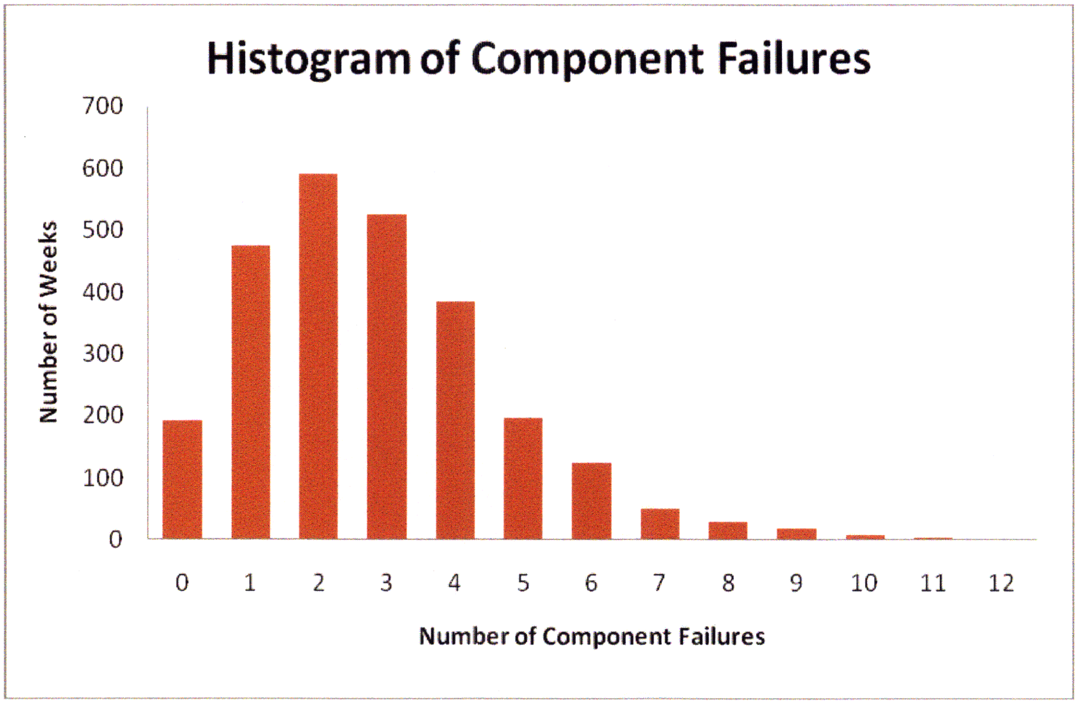


Figure 14 Histogram of Component Failures for 50 years

From Figure 14, it can be seen that no component failure occurred in about 8% of life time of a 100 turbine floating offshore wind farm. Similarly, 2 component failures occurred in about 24% of the time, equivalent to 591 weeks out of the 2600 week life span of the wind farm. It was observed that a maximum of 12 component failures occurred in 2 out of the 2600 week life span corresponding to just 0.1%.

4.3 Examination of Cannibalization Policy

Given the nearly weekly frequency of wind turbine component failures, a plausible maintenance policy that will "cannibalize" wind turbines is plausible. Cannibalization of wind turbine components involves restoring one or more failed wind turbine to operation by using component(s) from another failed wind turbine. Cannibalization is only possible when the different components are required for replacement on different failed wind turbines.

Cannibalization can be of the order of 1-2, 1-3, 1-4 and so on. For example in week 9 on Figure 13, of the 3 failed wind turbines, replacement components required were controller, inverter and a blade. By removing the functioning inverter and controller from the wind turbine with the failed blade, and replacing it with the failed components from the wind turbines, these two wind turbines can be brought back to electricity generating operation.

Cannibalization policy should be instituted when failures are unknown before a repair crew departure to floating offshore wind farms or when there are long lead times for wind turbine component order. The choice of maintenance strategy examined in 4.4 also dictates if a wind farm operator should cannibalize wind turbines.

A significant amount of cost savings can be achieved with cannibalization vs. non-cannibalization. By cannibalizing wind turbine components, each wind turbine restored to operation can generate revenue of about \$2.7 million per week and over \$0.38 million per day. This numbers were calculated from estimated annual revenues of \$138 million as discussed in Chapter 3.

4.4 Examination of Maintenance Strategies

As proposed by Rademakers, Braam, Obdam, Frahbose and Kruse (2008), three inventory policies to be considered in operating a floating offshore wind farm are:

- Calendar based maintenance

- Unplanned corrective maintenance
- Condition based maintenance

4.4.1 Calendar Based Maintenance

When employing calendar based maintenance strategy, the repair crew plans to visit the floating offshore wind farm once a week to ascertain the working condition of its wind turbines and replace damaged turbine components. While this maintenance strategy may reduce service levels, it does not require wind farm operators to carry inventory of replacement parts. Because wind turbine components are supplied by manufacturers in a one-to-many relationship, it is plausible that lead times would be low and therefore optimal for an operator to enter into fixed price contracts where manufacturers will provide total support solutions.

In practice inventory of wind turbine components will be transported to the offshore location using the jack-up rig which serves the dual purpose of both a hoisting equipment and storage for replacement parts. With a calendar based maintenance strategy, an overhaul of all turbines in the wind farm is recommended every 5 years to replace worn out parts and prevent catastrophic failures of wind turbines. A wind farm operator would not be required to own a jack-up rig when implementing calendar based maintenance strategy.

4.4.2 Unplanned Corrective Maintenance

For this maintenance strategy, it is recommended that an operator of a floating offshore wind farm own a self propelling jack up platform to be utilized in making unscheduled visits to the wind farm for corrective maintenance. Alerts such as reduction in electricity output can trigger a trip to the wind farm to examine failed wind turbines and determine wind turbine components needed for replacement. The reactive nature of this maintenance strategy as opposed to the static nature of calendar based maintenance strategy makes holding replacement parts inventory very necessary. The high service level attained by this maintenance strategy ensures reduced downtime of wind turbines and optimal electricity generation from the wind farm.

4.4.3 Condition Based Maintenance

As opposed to the unplanned corrective maintenance, the condition based maintenance strategy employs the use of remote monitoring devices such as sensors to monitor the health of wind turbine components and determine when replacement would be required. This strategy operates with information transmission via satellite to the wind farm operator before a repair crew makes a trip to the wind farm. The difference is between the high cost of satellite monitoring equipment which ensures that operators are aware of the required replacement parts to change out before each trip as compared to the low cost of screening electricity output for alerts and the possibility of multiple trips to the wind farm to get required wind turbine components. An advantage of condition based maintenance is the high service level obtained which ensures the wind farms generate installed electricity capacity all year round.

From the results of sections 4.1, it would be recalled that inventory holding cost is insignificant when compared to total cost of operating the floating offshore wind farm. Also from the simulation results in section 4.2, weekly maintenance would be required to maintain failed wind turbine components. It is therefore desirable for floating offshore wind farm operators to have a calendar based maintenance strategy that would require them to enter into fixed service contracts with turbine manufacturers. This will absolve them of the need to hold inventory at a cost of $3.7 million; own a self propelling jack up rig that would cost hundreds of millions of dollars; and retain high skilled labor required for a competent repair crew.

5 Conclusions

The results from this study were for a hypothetical 500 MW floating offshore wind farm comprising of 100 units of 5 MW wind turbines. From Chapter 3, average annual wind speeds were found to increase with distance from shore. After necessary adjustments were made to extrapolate wind speeds from an anemometer height of 4 – 5 m to a wind turbine machine hub height of 80 m, offshore wind speeds were found to range from 9 – 14 m/s. These modified wind speeds generated electricity output of between 6,500,000 kWh to 17,500,000 kWh.

Revenues from electricity sales at the prevailing market price of 10 cents/kWh resulted in sales of $80 million to $138 million for distances from shore of 3.51 – 55.24 miles. Because it is not certain that wind speeds will continue to increase with distance from shore, an assumption of a constant wind speed after 55.24 miles was made. Under this assumption, the cost of generating electricity from the floating offshore wind farm increases with distance from shore, it was found that it will be unprofitable to operate a wind farm after 145 miles.

Changing weather patterns show that locating the wind farm farther from shore may in some years negatively impact profitability. However, it does not suggest that offshore wind farms are unprofitable. Taking together, one can surmise that there might be an optimal distance from shore for a floating offshore wind farm as it does not seem reasonable to locate one in the middle of the Atlantic Ocean. Based on the data available, it may be impossible to forecast future weather patterns in order to determine with reasonable accuracy the optimal location for a floating offshore wind farm.

Inventory policy for a floating offshore wind farm was found to depend on the choice of maintenance strategy adopted by the operator. Instituting an inventory policy is necessarily challenging because of inclement weather conditions in an offshore environment and associated costs of maintaining the farm such as owning a self propelling jack up rig and retaining a competent repair crew.

Using failure rate data, inventory holding cost was found to be $3.7 million for a 4 week lead time and 99% service level; this cost was insignificant when compared with the total cost of about $100 million incurred in operating a floating offshore wind farm.

Simulation results indicate that failures occurred nearly every week, resulting to at least one failure per week in 92% of the 50 year life span of a floating offshore wind farm. This result suggests that a cannibalization policy will add revenue of up to $2.7 million to the electricity generating capacity by restoring a wind turbine to operation.

Of the three maintenance policies examined, calendar based maintenance strategy which requires contracting wind turbine component manufacturers to hold inventory and service the floating offshore wind farm under maintenance contracts was more attractive. This was because unplanned corrective maintenance strategy and condition based maintenance strategy requires holding inventory to the tune of $3.7 million. Perhaps more importantly is the higher fixed cost of equipment such as a self propelling jack up rig and retaining a highly skilled repair crew.

In future work, it will be interesting to obtain data on water depths at the measuring stations used for this study. This information will be useful in determining the appropriate cost of the tension leg platform support structure cost and the transmission cable cost. It will also be of interest to determine the marginal impact of an additional wind turbine on electricity generation, as well as its impact on revenue using wind turbine component failures shown in the simulation results.

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