Status Report on the Hull Offshore Wind Project

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American Wind Energy Association
Windpower 2007 Conference

Abstract

Hull, MA, is a remarkable Massachusetts coastal community: since 2001 the town's municipal light plant (HMLP) has owned and operated "Hull Wind I", the largest wind turbine (660 kW) that had been installed in the state up to that time. More recently (2006), HMLP installed a second, larger (1.8 MW) wind turbine, Hull Wind II. Now the town has begun in earnest a project that is intended to result in the installation of an offshore wind farm, with a capacity of approximately 14 MW. This paper provides a summary of the progress on the Hull Offshore Wind Project.

1.0 Background

The project discussed in this paper has two unique features, as least in the United States. First of all, it involves a community owned and operated wind energy facility. This facility will be the third in this community, and the combined capacity will supply a large fraction of the community's electrical requirement. Second, this third wind energy facility will be sited offshore. Accordingly, this discussion of the project background will consider the town of Hull itself and offshore wind energy, particularly at the community scale. Hull's location, at the southern side of Boston Harbor, is shown in Figure 1.

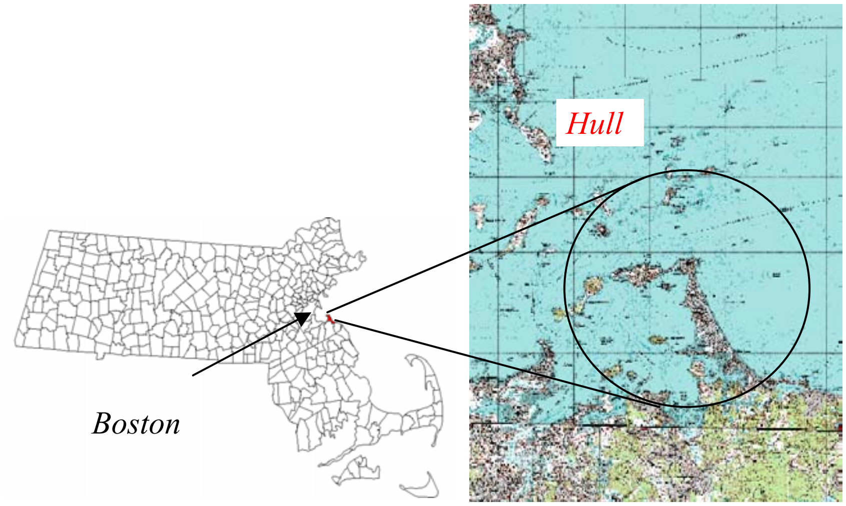


Figure 1 Location of Hull, Massachusetts

1.1 Wind Energy and the Town of Hull

The town of Hull has had a long history of utilizing wind energy. At least as early as the 18th century, and perhaps earlier, mechanical windmills were used at Windmill Point, which is at the easterly tip of the town, facing into Boston Harbor. In the early 1980's the Hull High School, located close to Windmill Point, installed a 40 kW Enertech turbine. In 2001, the Hull Municipal Light Plant (HMLP) installed at 660 kW wind turbine ("Hull Wind I"; see Manwell et al., 2004). This turbine supplies approximately 3% of Hull's electricity. In 2006, HMLP installed a 1.8 MW turbine ("Hull Wind II"; see Manwell et al., 2006). The two turbines together provide approximately 12% of the town's electricity. The locations of Hull Wind I and II are shown in Figure 2, which also includes an approximate location for the offshore wind project.

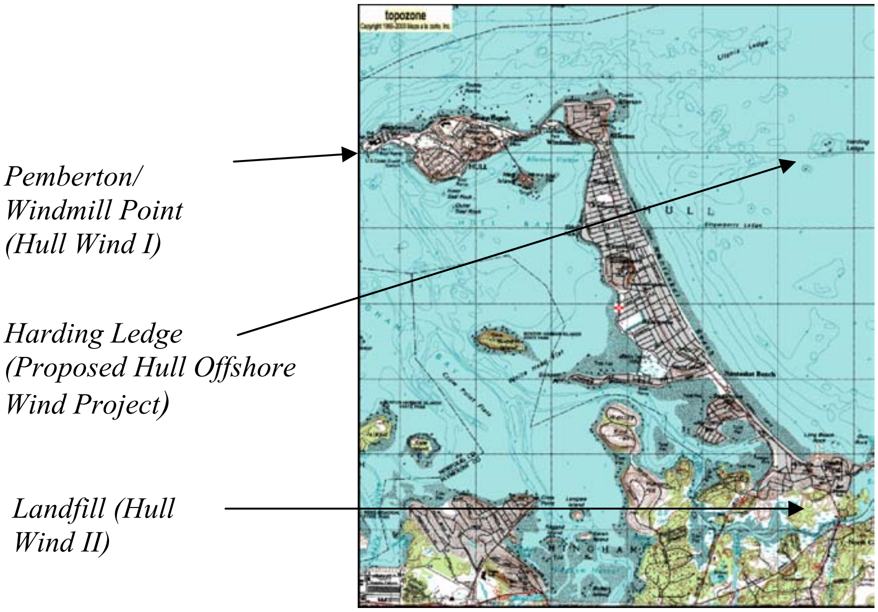


Figure 2 Locations of Existing and Proposed Wind Turbines in Hull

1.2 Offshore Wind Energy

As far as can be ascertained, the first concepts for offshore wind turbines originated in Germany with Hermann Honnef (Honnef, 1939). The next proposals for offshore wind turbines were advanced by William Heronemus at the University of Massachusetts in the early 1970's (see Heronemus, 1972). None of these early concepts made it beyond the drawing board, however. It remained for wind turbines to work sufficiently well on land for the designers to begin serious consideration of installing turbines offshore. The first group of offshore turbines was installed at Vindeby in Denmark in 1991. That project is located approximately 1.5 km offshore in water depths of 3-6 m. It consists of 11 turbines, each rated at 450 kW, for a total capacity of 4.95 MW. Over the last 15 years offshore wind energy has continued to be developed. There are now at least 25 installations in the world with a total capacity of just under 1.6 GW; so far all of them are in Europe (Moeller, 2007).

There has been an apparent trend recently in offshore wind energy development towards both larger turbines and larger projects. This is because the cost to produce electricity from offshore wind turbines has so far been greater than that of onshore turbines, making the economics more problematic. Overall cost of energy can be brought down by using larger wind turbines and spreading the fixed costs over a greater number of machines.

In spite of a general trend towards larger offshore wind projects, there has been and there remains a significant potential for community scale projects as well. Such projects can be attractive when the power can be used locally and thus has a higher value. Certain aspects of the installation cost can also be reduced because community scale projects may often be sited closer to shore than larger projects. Examples of projects of this type include the Middelgrunden and Samsoe offshore wind farms in Denmark. The Middelgrunden project consists of twenty, 2 MW wind turbines, and is located approximately 1.5 km off Copenhagen in water depth of 3-6 m (http://www.middelgrunden.dk/MG_UK/project_info/mg_pjece.htm). The Samsoe wind farm consists of ten 2.3 MW turbines and lies 3.5 – 6.5 km off the island of Samsoe in water depth of 14-20 m (Bjerregaard et al., 2005). Both of these projects have ownership structures which are somewhat similar to what may be applicable to Hull. For example, the Samsoe wind farm is owned 50% by the municipality of Samsoe and 50% by private investors. Similarly, Middelgrunden is owned partially by a cooperative and partially by the Copenhagen municipally owned electrical utility.

1.3 Background of the Hull Offshore Wind Project

The Hull Offshore Wind Project has a variety of antecedents. The first of these was an investigation in the late 1990's of the potential of offshore wind energy in Massachusetts. This investigation was carried out by the by the Renewable Energy Research Laboratory (RERL) at the University of Massachusetts, with support from the Massachusetts Division of Energy Resources (Rogers et al., 2000). The next was consideration of the Middelgrunden offshore wind project mentioned above as a possible model (Manwell, 2002). Then during the planning stage for the Hull Wind II project, installing offshore wind turbines was also seriously considered (Manwell, 2003). At that time it was decided to proceed with the second land based turbine, but to pursue the offshore option for the future (Manwell, 2004). Towards this end, in the fall of 2003 the first steps were taken towards acquiring the permits to install a single offshore turbine. These steps included the conceptual description of the installation and initial discussions with the US Army Corps of Engineers and state officials regarding the permit applications.

In 2005 the Massachusetts Technology Collaborative (MTC) offered to consider an application from the RERL and the Town of Hull for funding to undertake detailed technical studies in support of the offshore wind project. By the this time, the Town Light Board had decided to consider up to four offshore wind turbines in the size range of 3.6 MW each. The project was also envisioned to be able to serve as an example that would facilitate the development of a "best practices" plan for the development of offshore wind project in Massachusetts waters. Accordingly, in August of that year the RERL and Hull prepared an application entitled "Proposal by the University Of Massachusetts Renewable Energy Research Laboratory and the Hull Municipal Lighting Plant to the Massachusetts Technology Collaborative for Support of HMLP's Offshore Wind Turbine Project and Best Practices for Site Selection, Design and Installation of Offshore Wind Turbines."

Upon further consideration, the MTC decided that the best way to move forward was to offer the Town of Hull a forgivable loan to support many of the same investigations that were intended to be undertaken as outlined in the first proposal. A second proposal for funding was then prepared in March of 2006. This proposal originated from the Town of Hull itself, and was directed specifically "for support of HMLP's offshore wind energy project." Following one more revision of the proposal in August of 2006, the request for funding was approved by the MTC board in the fall of 2006.

2.0 The Proposed Hull Offshore Wind Project

The Hull Offshore Wind Project, as described in the final proposal and as presently envisaged, is to include up to four offshore wind turbines, with a total generating capacity of up to 14.4 MW. The location for the turbines is to be in the vicinity of Harding Ledge, which is located approximately 2.5 km off the east coast of Hull (Nantasket Beach). The water depth in this area is in the range of 12-15 m.

A number of turbines are being considered for the project. The most likely options at this point are turbines in the capacity range of 3.0-3.6 MW, with diameters of between 90 and 106 m.

Figure 3 shows some location options for the turbines and the electrical cable to shore. The turbines themselves would be in or on the edge of the kidney-bean-shaped area to the easterly side of the region enclosed by the heavy black line. The electrical cable would go through the left side of that region from the turbines to the shore, depending on the location of the turbines, the most suitable interconnection point on land, and the nature of the seabed.

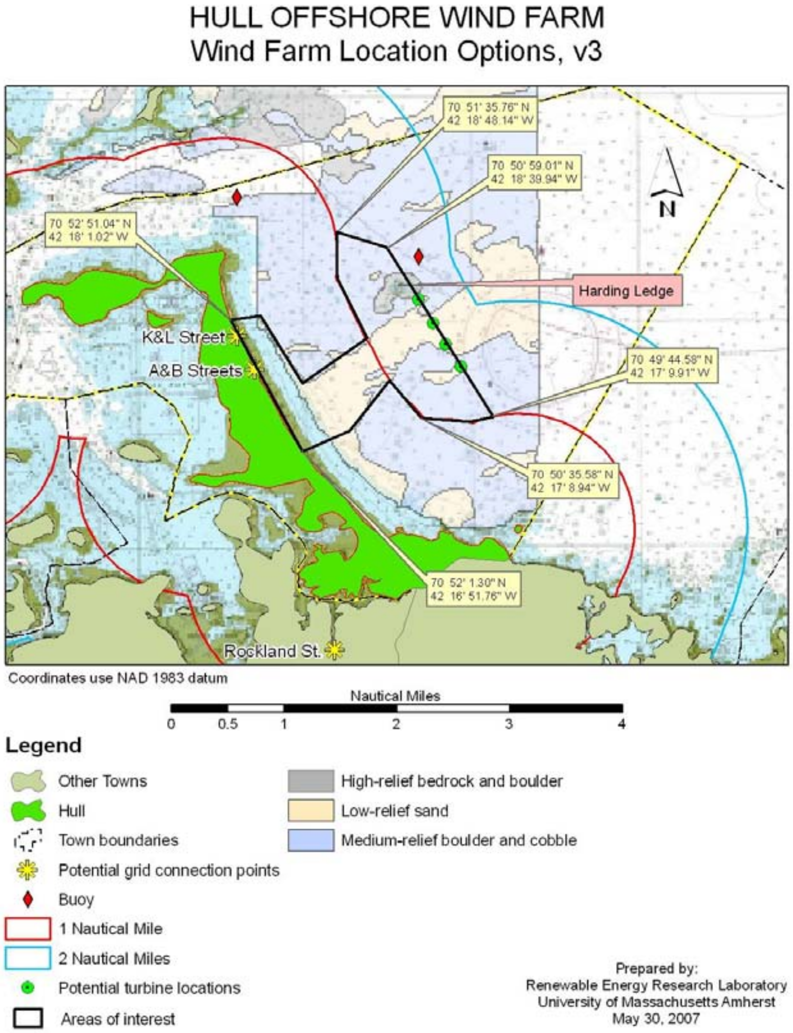


Figure 3 Area of Interest for Hull Offshore Wind Project

The project is currently in the feasibility and permitting stage. Activities that are underway include meteorological-oceanographic investigations, a variety of sub-sea studies, site layout planning, and preliminary design of the support structures. The participants in the project include HMLP (http://www.town.hull.ma.us/), the RERL (http://www.ceere.org/rerl), ESS Group Inc. (http://www.essgroup.com/), AMEC Paragon (http://www.paraengr.com/), GZA GeoEnvironmental Inc. (http://www.gza.com/), MIT's Laboratory for Energy and the Environment (http://lfee.mit.edu/metadot/index.pl), and the department of Civil Engineering at the University of California at Davis (http://cee.engr.ucdavis.edu/). Financial support (in the form of a loan) is being provided by the Massachusetts Technology Collaborative's Renewable Energy Trust Fund (http://masstech.org/renewableenergy/index.htm).

Tasks being undertaken under the direction of the RERL include: (i) overall technical coordination, (ii) characterization of meteorological and oceanographic external conditions (for performance estimates and inputs to the design basis), (iii) wind farm layout and feasibility assessment, (iv) preliminary investigations into the design of the support structures and installation of the turbines, and (v) environmental benefit identification. Task (iv) above also involves the participation of AMEC Paragon, GZA and UC Davis. Task (v) includes the participation of MIT.

Permitting and environmental studies are under the purview of ESS. ESS's tasks include the following: (i) preliminary siting and permitting evaluation, including evaluation of regulatory strategy and schedule, (ii) geophysical and geotechnical assessment as related to permitting, (iii) evaluation of routes for the submarine cable, (iv) preparation of permit application, and (v) assistance with community outreach.

This paper focuses on the activities with which the RERL is most directly connected.

3.0 Overall Technical Coordination

This task involves coordination among all the various parties. Efforts to date have primarily involved helping to get the various subcontracts in place and facilitating discussions between the different parties involved. This task also includes providing input to the permitting process as needed and assisting with community outreach.

3.1 Permitting

The proposed Hull Offshore Wind Project will be exclusively within the state waters of Massachusetts, and accordingly the permitting involves primarily state agencies, rather than the Minerals Management Services (MMS). The US Army Corps of Engineers will be involved, however, since the offshore wind turbines will be constructed within navigable waters of the US. Since MMS is not involved, it presently appears that there is no requirement on which design guidelines will be used for the offshore turbines and their support structures. It is presently intended that the project will be developed in accordance with the recommendations of the IEC 61400-3 offshore wind turbine design standards (IEC, 2006). The permitting process has just begun, and as previously noted is primarily under the purview of ESS. RERL's role in this process includes helping to ensure consistency among the various studies that will have relevance to aspects of the project beyond that of permitting alone. These include site layout, feasibility assessments and support structure design.

3.2 Community Outreach

An important aspect of the early phases of the Hull Offshore Wind Project is to keep the public informed. Over the last few years there have been meetings of the Light Department at which the project was discussed and there were articles in local newspapers. More recently (February, 2007), a public informational meeting was held at the Hull High School. Since one of the concerns people sometimes have about wind energy projects has to do with visual impacts, a number of photosimulations were created and included in the public presentations. One of these is shown below in Figure 4. All of the presentations from the February meeting are available at http://www.town.hull.ma.us/Public_Documents/HullMA_Light/offshore

Figure 4 Example Photosimulation of Hull Offshore Wind Project

4.0 Characterization of Metocean Conditions

An understanding of the meteorological-oceanographic (metocean) conditions is needed for two reasons: (1) to evaluate the economic feasibility of the proposed project and (2) to prepare the design basis of the wind turbines and their support structure. The primary determinant of the economic feasibility of the project is the wind resource. As with onshore projects, characterization of the wind resource is via time series wind data, averaged over 10 minute intervals. For the design of the wind turbines, as well the 10 minute means, simultaneous time series of wind direction and turbulence intensity are also of interest. Extreme winds, such as those with a recurrence interval of 50 years, must also be estimated. In addition to the wind information, characterization of the wave and current conditions at the site is also required. This includes significant wave heights, wave period, and wave direction. Ideally time series data is obtained, concurrently with the corresponding wind data, for at least one year. Also, as with wind speed, 50 year extreme waves must also be estimated.

The metocean conditions to be expected at Hull are presently under investigation. This is being done by considering current and historical data from a number of observation stations in the vicinity and by collecting data within Hull itself, close to the site of the proposed wind project. Existing observation stations being used include Blue Hill Observatory in Milton, MA (42.249°N/71.066°W); Boston's Logan Airport (42.36297°N/71.00642°W); the National Data Buoy Center (NDBC) Buoy 44013, located outside Boston Harbor, approximately 18 km NNE of Harding Ledge, at 42.35389°N/70.69139°W; a meteorological tower on Thompson Island in Boston Harbor (42.315°N/71.0124°W); and instrumentation on one of the WBZ towers in Hull (42.2789°N/70.8762°W). Hindcast data from the US Army Corps of Engineers is also being used (see http://frf.usace.army.mil/cgi-bin/wis/atl/atl_main.html).

Wind data is presently being collected on a 10 m tower with a conventional anemometry and with a LIDAR at Little Brewster Island (42.328N/70.89W) and wave data is being collected close to Harding Ledge with an acoustic Doppler profiler. More detail is provided below.

4.1 Wind

The wind resource in the vicinity of Harding Ledge has been estimated in a preliminary fashion by taking advantage of existing data and applying a measure-correlate-predict algorithm (Rogers et al, (2005). Data from multiple heights on the WBZ tower in Hull was used to estimate the wind shear in the vicinity and then the AWS TrueWind map (Figure 5) was used to extrapolate to the offshore site. The estimate obtained in this way is that mean annual wind speed at 80 m above sea level at Harding Ledge is approximately 8 m/s. This estimate will be further refined as more data from the LIDAR now located on Little Brewster Island (see below) becomes available.

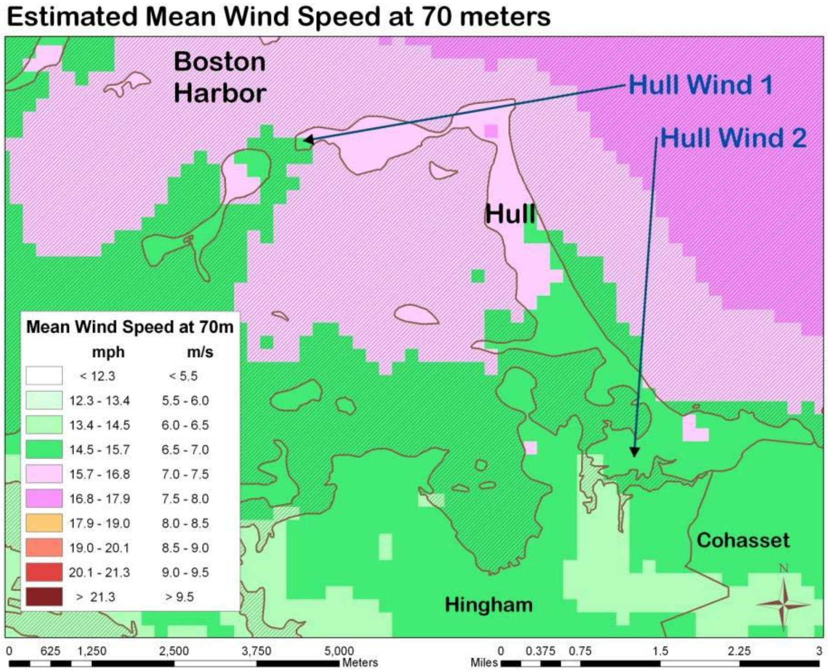


Figure 5 AWS TrueWind Windspeed Estimates for Hull

4.1.1 Wind Data Collection

Wind data is being collected in a variety of locations in the vicinity of Hull. Of particular relevance is the monitoring underway on Little Brewster Island. This uses both conventional anemometry and LIDAR. The location of this monitoring is shown in Figure 6. Conventional anemometry is measuring the wind at 10 m above ground level (a.g.l.) The LIDAR is presently measuring data at 10, 60, 80, 100 and 120 m a.g.l.

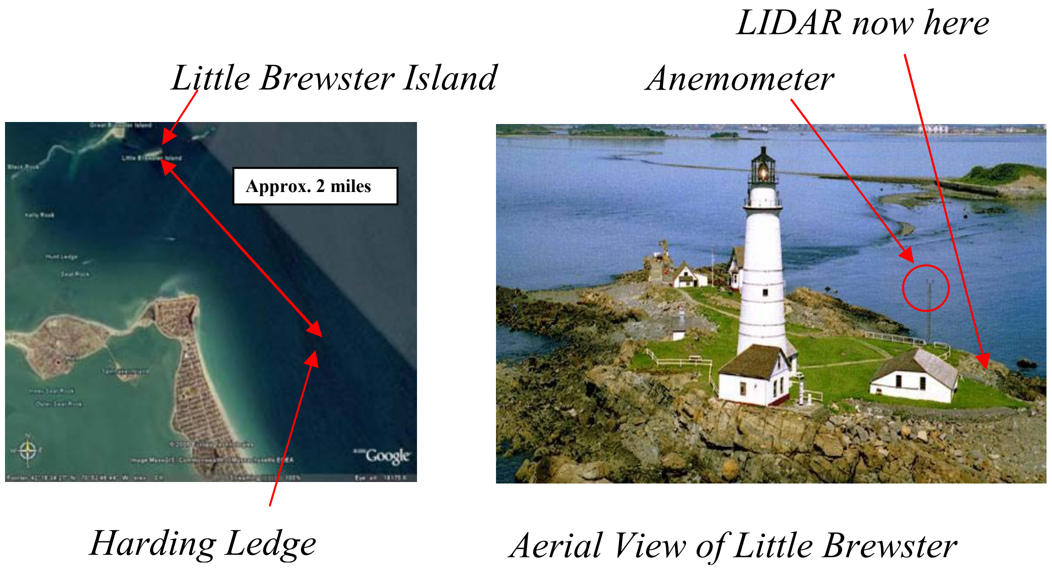


Figure 6 Data Collection on Little Brewster Island

Before the LIDAR was installed on Little Brewster Island, an extensive wind monitoring test program was carried out. During this study, measurements from the LIDAR were compared with the results of conventional anemometry installed on a tall radio tower in Hull. Tall tower measurements were taken at elevations as high as 118 m a.g.l. The tall tower and some results of the comparison are illustrated in Figure 7. A wind rose based on data from this site is shown in Figure 8. More details are available in Jaynes et al. (2007).

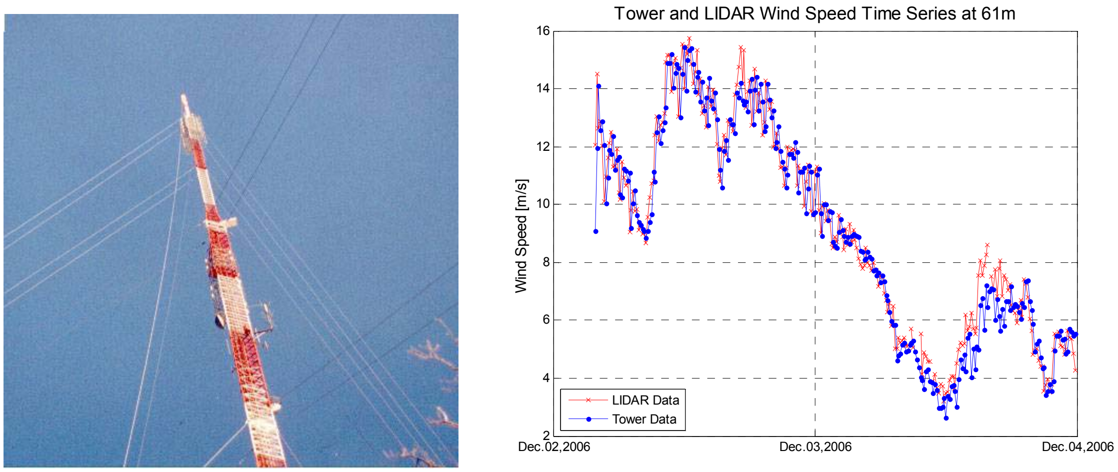


Figure 7 WBZ Tower and LIDAR/WBZ Data Comparisons

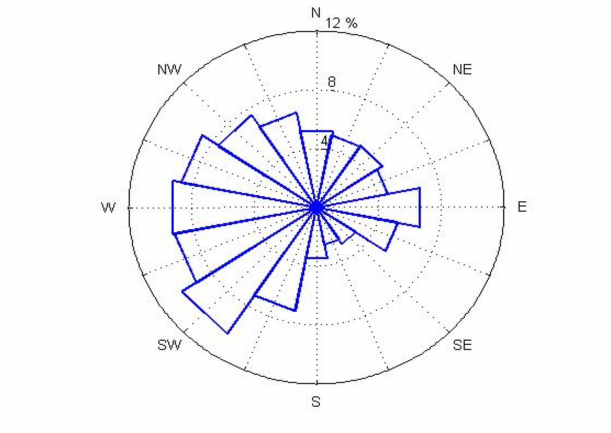


Figure 8 Wind Rose at WBZ Tower

4.1.2 Maximum Wind Speeds

It is necessary to have an estimate of the extreme winds likely to be encountered at the site. These are used in the design of the turbines and their support structures. Estimation of the extreme winds is still underway, but some of the available data relevant to this are summarized in Table 1. These data suggest that the highest 10 minute average wind speed that is likely to occur just once in 50 year (technically known as the "expected extreme wind, with a recurrence period of 50 years") will be on the order of 40 m/s or more, and that the 50 year extreme gust will be correspondingly higher.

Table 1 Selected Maximum Wind Speeds in Vicinity of Hull, MA

Location	Observation Type	Observation	Units	Period
Buoy 44013	Max. 8–min average wind speed	25.8	m/s	1984-present
Buoy 44013	Maximum wind gust	34.5	m/s	1984-present
Blue Hill Observatory	Maximum wind gust	56	m/s	1940-present
Blue Hill Observatory	Maximum wind gust	83	m/s	1885-present

4.2 Waves

Understanding the wave climate is critical to the design of the wind turbine support structures. Data is being collected on site, and will be augmented by long term wave data available from NDBC Buoy 44013. A typical NDBC buoy is illustrated in Figure 9. Some the data that are available from Buoy 44013 are illustrated in Figures 10-13.

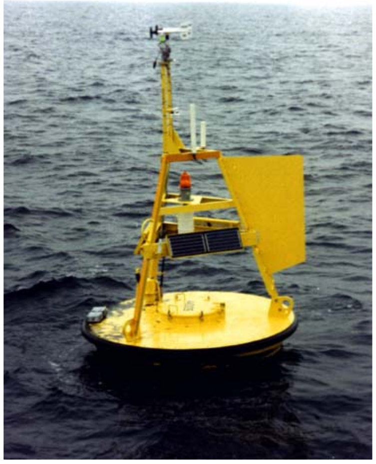


Figure 9 Typical NDBC Buoy

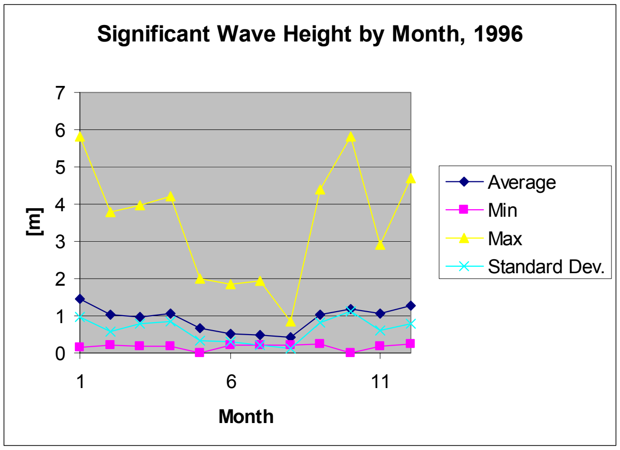


Figure 10 Significant Waves by Month at Buoy 44013, 1996

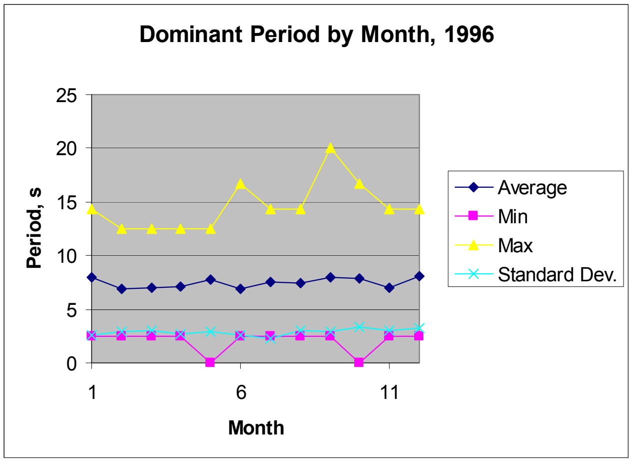


Figure 11 Dominant Wave Periods by Month at Buoy 44013, 1996

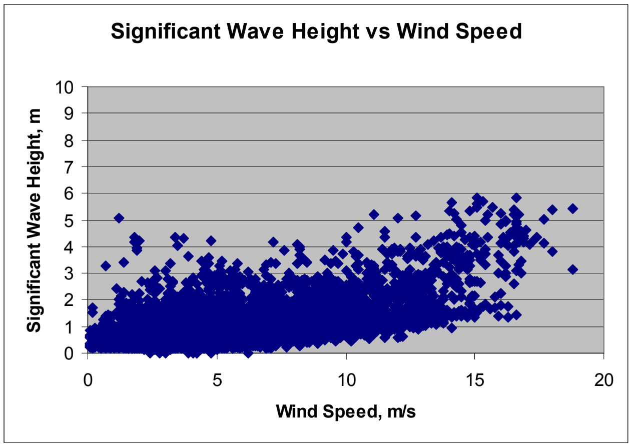


Figure 12 Significant Wave Height vs. Wind Speed at Buoy 44013, 1996

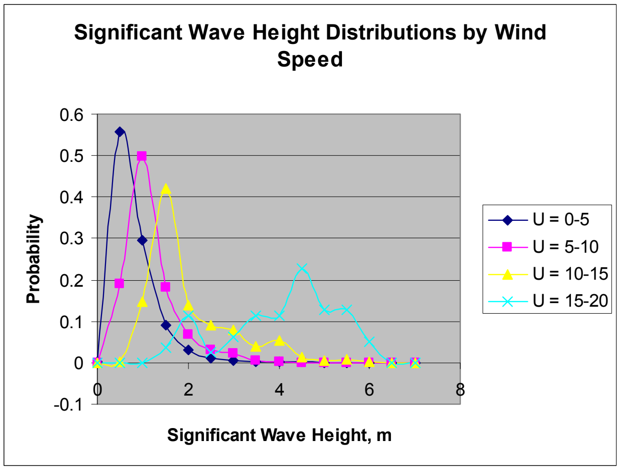


Figure 13 Wave Height Distributions by Wind Speed, U, (m/s) at Buoy 44013, 1996

The wave climate will be somewhat different at Harding Ledge than at Buoy 44013. Hindcast methods can be used to estimate what the maximum waves and their corresponding periods are likely to be. The preliminary estimates are shown in Table 2 below.

Table 2 Preliminary Estimates of Maximum Waves at Harding Ledge

Situation	Observation	Units
Max. sig. wave height	6.1	m
Corresponding period	9.9	s
Max. sig. wave height @ wind = 12 m/s	1.7	m
Corresponding period	5.2	s

4.2.1 Wave Data Collection

In addition to considering the wave data from NDBC buoys, it is necessary to collect data close to the proposed site. This will allow better estimates of the actual wave conditions, and it is also consistent with the IEC offshore wind turbine design standards (IEC, 2006). We are presently taking wave data off Nantasket Beach with a Sontek acoustic Doppler profiler. Such devices are described in detail by the manufacturer (http://www.sontek.com/adp-family.htm). The principle of operation is that sound waves are emitted from the device in three beams. Reflected waves are received from various locations in the water and analyzed within the device to determine the parameters of interest. The beams are illustrated in Figure 14 below. The deployment of the ADP in Hull (protected by an anti-trawl device) is illustrated in Figure 15.

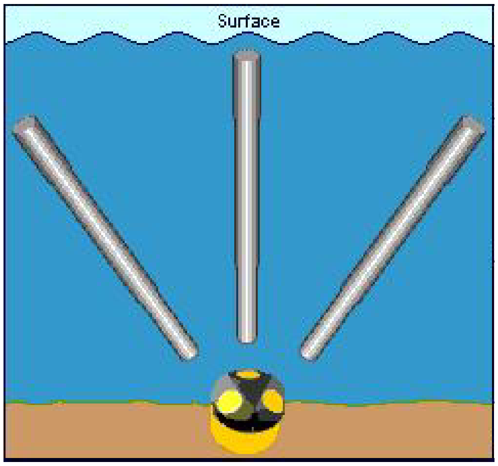


Figure 14 Principle of Operation of ADP

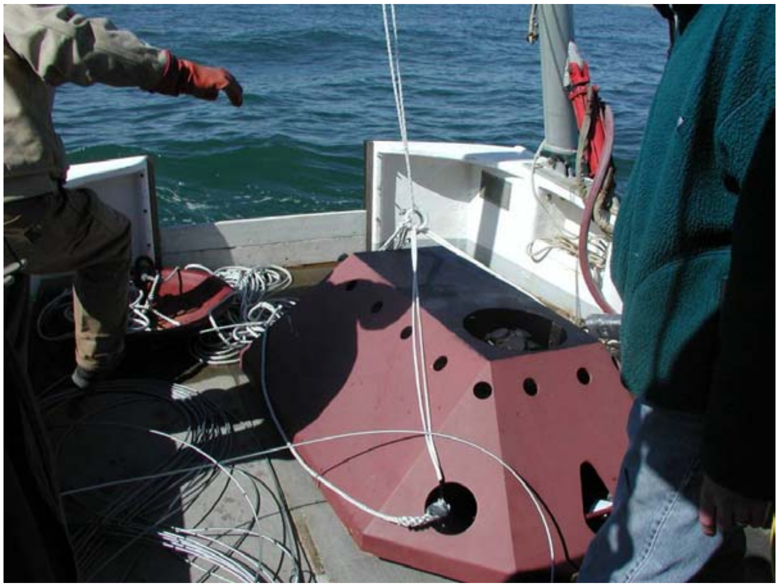


Figure 15 Deployment of ADP off Hull

Some results of the data collection are shown in Figure 16 below. A web cam photograph shows the sea conditions immediately off the beach during an April, 2007

Northeast storm (April 16-17). The time series shows water level variation during the same storm. Note that the data is reported in decibars, and that one decibar corresponds very nearly to 1 m of seawater. An illustration of wave directional data is shown in Figure 17; in this example, the significant wave height is 2.54 m and the peak period is 8.3 s. As is apparent from the figure, most of the waves are from the NE.

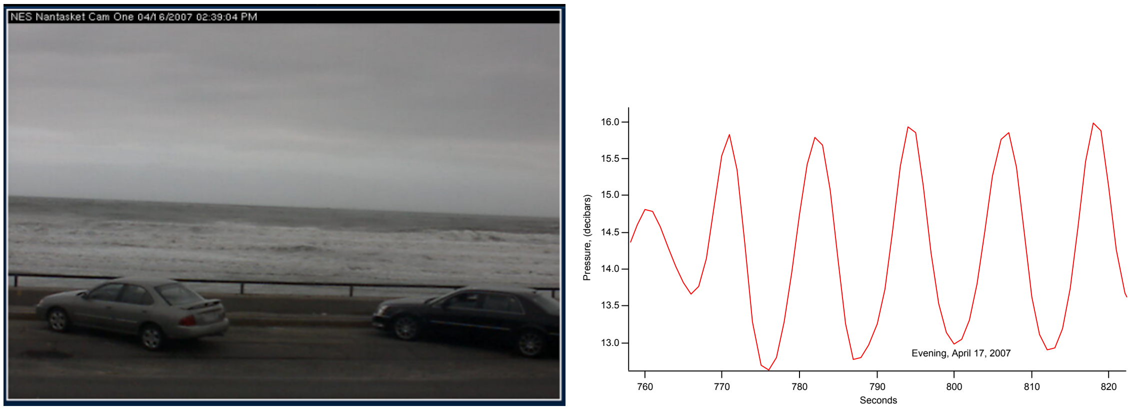
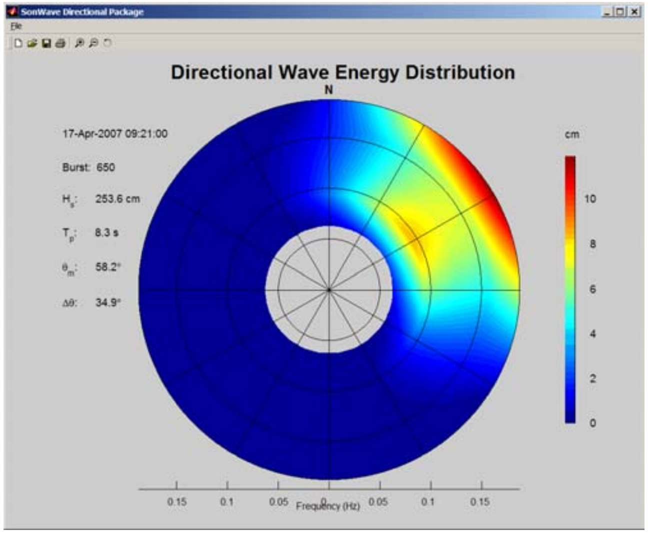


Figure 16 Waves and Wave Data during April Storm in Hull



17-Apr-2007 09:21:00

Burst: 650

H_s: 253.6 cm

T_p: 8.3 s

θ_m: 58.2°

$\Delta\theta$: 34.9°

Figure 17 Directional Wave Data during April Storm in Hull

Figure 18 shows a comparison of significant waves heights measured at 44013 and with the ADP off Hull. The comparison is over an approximately one week period.

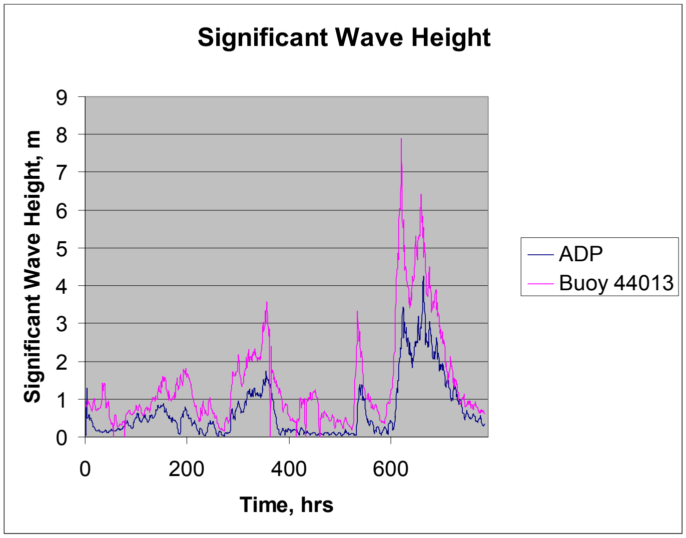


Figure 18 Sample Wave Data from Buoy 44013 and the Hull ADP

5.0 Wind Farm Layout and Feasibility Assessment

Wind farm layout refers to the actual placement of the wind turbines. Closely connected to the layout is feasibility assessment. This refers to an investigation into the relative cost of energy from the turbines and the value of the electricity that they would produce.

5.1 Wind Farm Layout

In selecting a wind farm layout is desirable to locate the turbines in an as economically optimal way as possible. That is to say the cost of production of the electricity from the turbines should be as low as is practical. To facilitate this process an offshore wind energy layout optimization tool has been developed and applied to the Hull offshore wind project (see Elkinton et al., 2006). This tool was used to help choose the area of interest illustrated above in Figure 3.

5.2 Feasibility Assessment

5.2.1 Cost of the project

Detailed estimates of the cost of the project are in the process of being made. Important considerations are the costs of the turbines themselves, their support structures, and the electrical cables to shore. Other concerns are the installation costs, and once the turbines are operating, the cost to operate and maintain them.

Based on discussions with various manufacturers, we anticipate that it will be possible to purchase and install the wind turbines for a cost of approximately $2,500/kW.

5.2.2 Wind Farm Electricity Production and Consumption

A project of the size discussed in this paper will produce, on the average, an amount of electricity close to that used in the town. Due to mismatches between the load and the wind, there will be times when all of the electricity can be used in town and other times when the production will exceed that the town’s demand. In the latter case, some of the electricity will be sold outside of town. Figure 19 illustrates a hypothetical year of energy production and consumption using hourly data. The electrical data is based on that from Hull in 2003 (averaging 6.26 MW). It was then scaled up by 12.8% to consider one of the options of a sea water desalination plant which is being considered by the town. The average electrical load in this case was 7.06 MW. The wind speed data was based on measurements from nearby Thompson Island, but scaled to have a mean of 8 m/s. The turbines used were rated at 3.6 MW. In this example, with the increased electrical load, the total wind generation from the 4 offshore wind turbines and the 2 land based turbines would correspond to 85.7% of the total electrical load. In this case, 66% of the wind generated electricity would be used within the town and 34% would be sold. The average power from the offshore turbines alone would be 5.36 MW (corresponding to a capacity factor of 37.5%). Note that in this example, the availability was assumed to 100%.

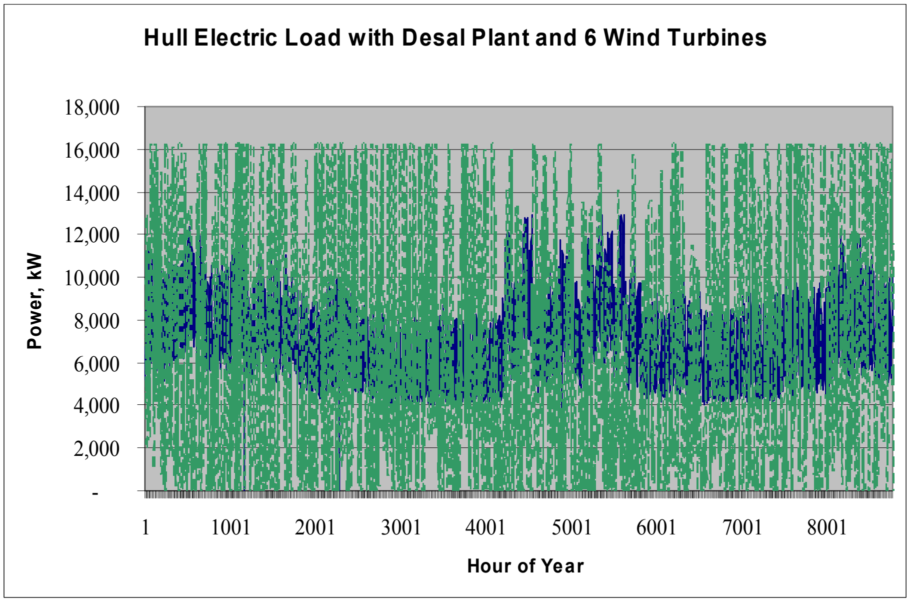


Figure 19 Sample Hourly Power Generation and Use

One additional topic of interest concerns the capacity of Hull's electrical network in comparison to the proposed offshore wind farm. At the present time, the peak hourly electrical load in Hull is approximately 12 MW. During periods of high winds, there could be sustained generation within the town of 16.9 MW. Taking into account the town's electrical load, there could be a number of periods during the year when the net export of power from the town could exceed 10 MW. Preliminary investigation indicates that the capacity of the network is sufficient to accommodate all the generation that is being considered, at least on a quasi-steady state basis. It remains to be determined what, if any, modifications would be needed to ensure grid stability under all plausible eventualities.

5.2.3 Economic Analysis

At this stage in the process, a precise assessment of the economic viability of the proposed Hull offshore wind project is not possible. Nonetheless it is possible to make some reasonable estimates. Furthermore, based on the available wind data, we expect that the average wind speed at hub height will be on the order of 8 m/s (as used in the example above). HMLP presently purchases electricity for distribution in town at a price of $0.125/kWh. As indicated previously, some of the generated electricity would be sold. For this example we will use the percentages obtained above; that is 66% will be used in town, 34% will be sold Assuming that the electricity could be sold for half of the price for which it could be purchased, the weighted average value of the electricity would be $0.10375/kWh.

A simple economic analysis was performed, using the assumptions shown in Table 3.

Table 3 Assumptions for Economic Example

Item	Value
Total rated power	14.4 MW
Installed cost	$2500/kW
Capacity factor (100% availability)	0.372
Availability	0.95
Fraction electricity used in Hull	66%
Fraction electricity sold	34%
Value of electricity used in Hull	$0.125/kWh
Value of electricity sold	$0.0625/kWh
Average value of electricity	$0.10375/kWh
Down payment fraction	0.2
Loan period	10 yrs
Project economic life	20 yrs
Bond interest rate	5%
Discount rate	3%
Inflation rate	2%
Operation/maintenance cost	$0.02/kWh
Value of renewable energy credits	$0.03/kWh

Under the above assumptions, the project would have a simple payback period of 7.1 years. The levelized cost to generate the electricity would be $0.083/kWh, and the cumulative net present value of savings to the town over the project lifetime would $52.6 million. This would be above the levelized cost of the project (including all costs above, which would be paid for as well) of $55.1 million. These results would change if the assumptions changed, but a preliminary sensitivity analysis indicates that the project could still be economic even with higher costs and lower winds.

6.0 Support Structure Options

The options for the offshore wind turbine support structures at Hull include monopiles, tripods (or similar structures) or gravity foundations. Which type is ultimately chosen will depend on the cost, which in turn will be influenced by the water depth and the geophysical conditions found at the site. Figure 20 shows a schematic of the possible types of support structures design options and the nomenclature used in the offshore wind industry. Note that the support structures illustrated, from left to right, are a monopile, a tripod, and a gravity foundation. Characterizations of the water depth and geophysical conditions are described below.

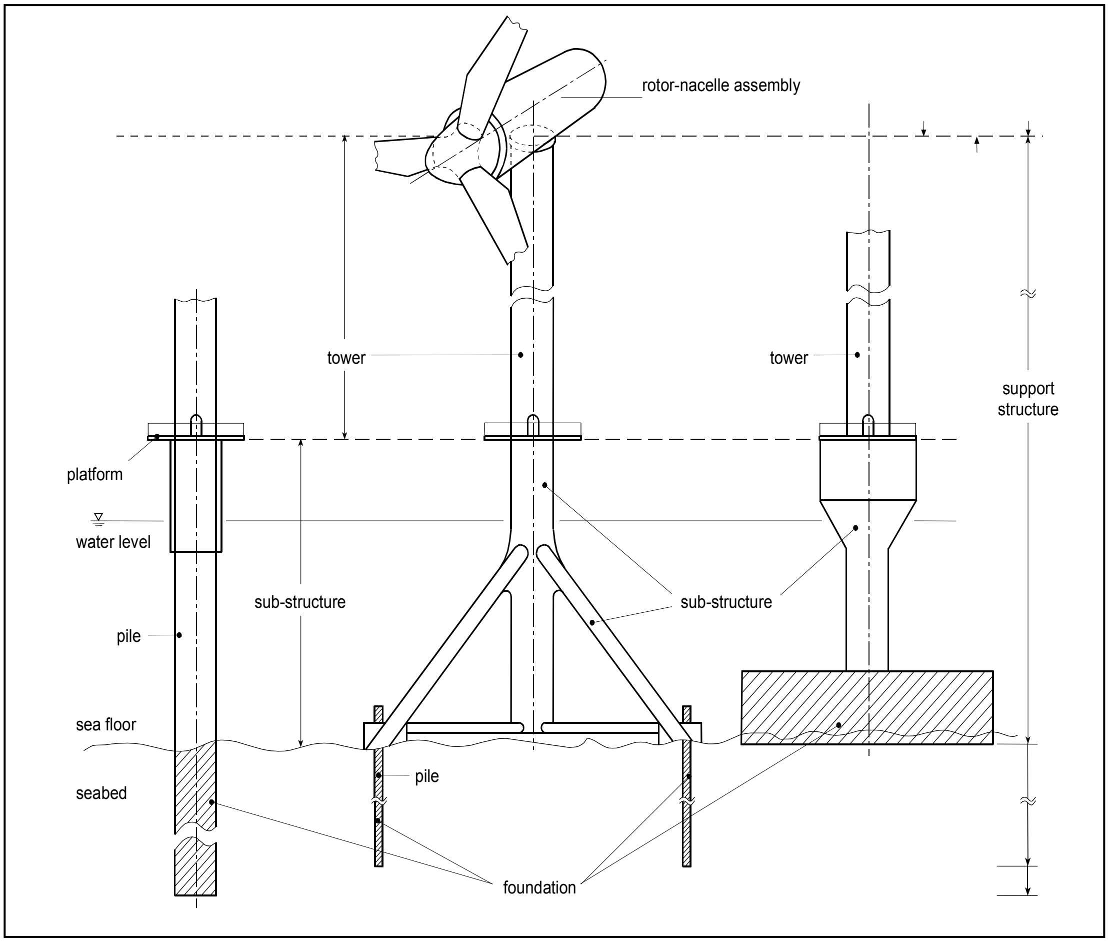


Figure 20 Definitions of Offshore Wind Turbine Components (IEC, 2006)

6.1 Bathymetry off Nantasket Beach

Bathymetry refers to the depth to the sea floor, relative to sea level. Water depth is an important factor to consider in the design of an offshore wind project, since it affects the type of support structures used and their cost as well as the method and cost of installation. Nautical charts indicate that the water depth off Nantasket Beach in Hull range from very shallow to approximately 20 m. A graphical illustration of water depth in this area is shown in Figure 21. This figure is a shaded-relief bathymetric map showing elevated areas and a sand “highway”, east of Nantasket Beach. The darker patches indicate the areas where multibeam bathymetry was collected and the data gridded at 2 m; the rest of the area was mapped by single-beam sonar and the data gridded at 30 m. This map is from (Ackerman et al, 2006). This reference also shows companion sidescan-sonar images and photographs at stations 5, 6, 8, and 10 on the map.

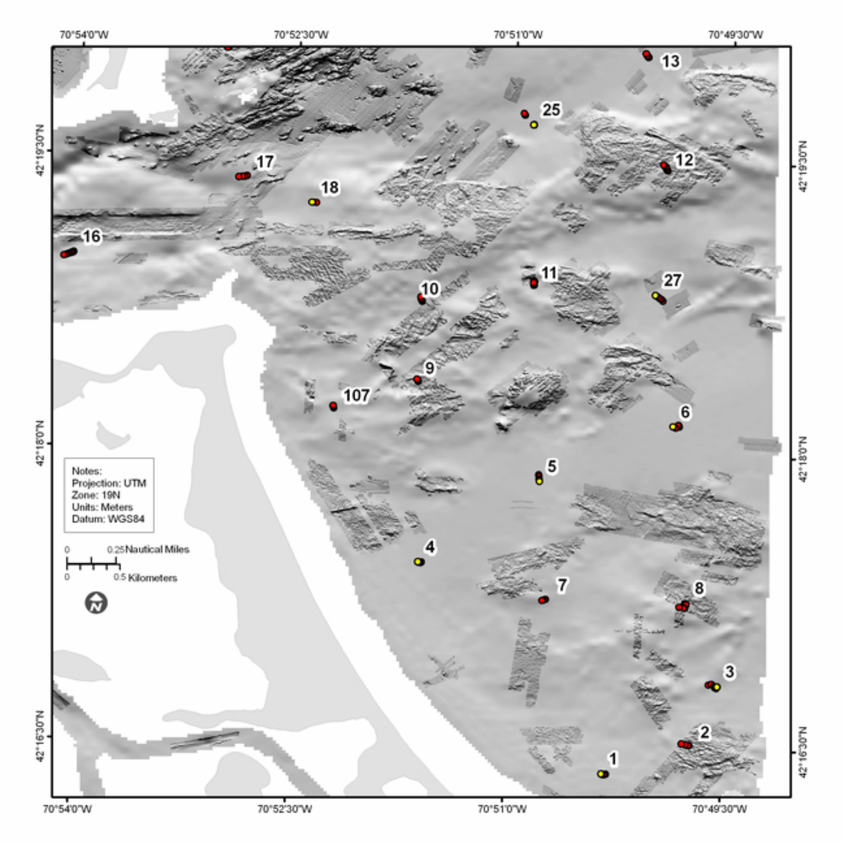


Figure 21 Shaded Relied Bathymetric Map off Hull

6.2 Geophysical Conditions at the Area of Interest

The geophysical condition of greatest interest is the soil type. The soil in the vicinity of Harding Ledge appears to be mostly mixed unconsolidated sediment of varying depth over bedrock. This conclusion is based on a study of the sediment from sub-bottom profiling results at a few near-shore locations. An example of these is illustrated in Figure 22. This data was obtained as part of study of the options for building a sea water desalination plant in Hull. In Figure 22, the vertical grid spacing is 6.1 m (20 ft), and the samples were taken approximately every 61 m (200 ft). The heavily dotted line shows the transition from glacial till or other unconsolidated sediment to bedrock. One thing to note is that in this transect, the depth from the ocean floor to bedrock varies from approximately 6 m (20 ft) to 18 m (60 ft) over a distance of 427 m (1400 ft), indicating significant variability in the characteristics of the ocean sub-bottom.

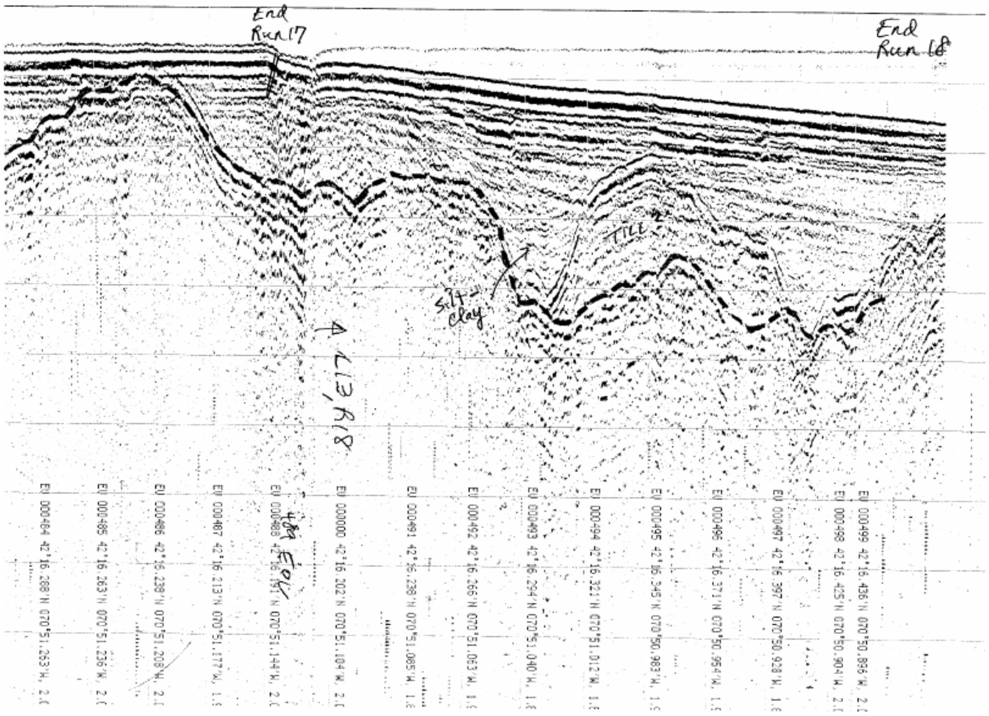


Figure 22 Typical Sub-bottom Profile in Vicinity of Nantasket Beach

More details are scheduled to be obtained shortly, first from additional sub-bottom profiling and later from drilling. Once the sub-surface investigation has been completed, and the final site options have been further narrowed down, borings will be done at some selected locations. These will be done at the most promising sites for the wind turbines. A typical vessel which does such borings is illustrated in Figure 23. For the case of Hull, however, due to the relatively shallow waters, a jack-up barge may be used rather than a vessel such as is shown here.

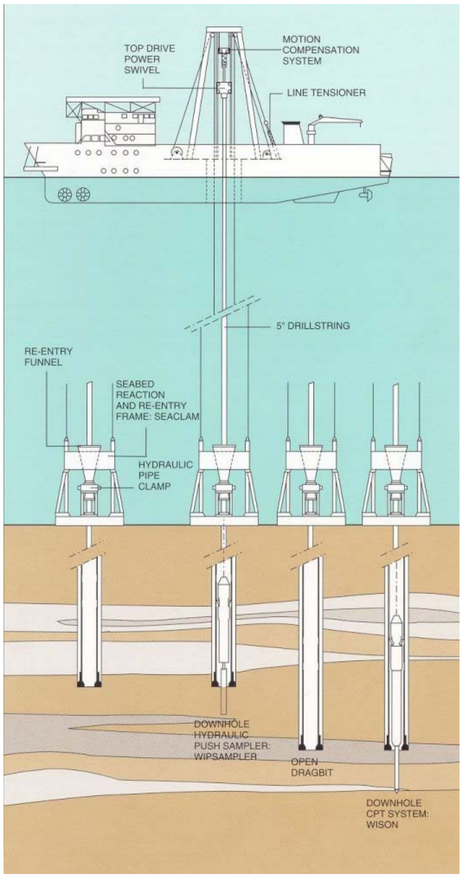


Figure 23 Typical Vessel For Seabed Investigations (www.fugro.com)

6.3 Loads on Wind Turbine Support Structure

This section describes a preliminary investigation into the design of the wind turbine and support structures. For this study we have selected a "base case" turbine and some variants of that base case turbine. The base case turbine has a rotor diameter of 90 m and is rated at 3 MW. More details on the base case turbine are included in Table 4.

Table 4 Summary Characteristics of Base Case Hull Offshore Wind Turbine

Characteristic	Value	Units
Rated power	3.0	MW
Rated wind speed	15	m/s
Cut-out wind speed	25	m/s
Rotor diameter	90	m
Tower height	80	m
Nacelle weight	70	metric tons
Rotor weight	40	metric tons
Tower weight	160	metric tons

In order to give a sense of wind turbine load characteristics, two simulations have been run using the GH Bladed software (http://www.garradhassan.com/products/ghbladed/) that can model the dynamics of an offshore wind turbine. This turbine modeling software package is capable of simulating the dynamics of a full wind turbine including the tower, sub-structure and foundation, when exposed to turbulent wind and random waves. In this case it was used to simulate just the loads from the wind turbine on the sub-structure at the tower base/sub-structure interface. In this case, a variant of the base case turbine was considered. This one was developed by taking advantage of the availability of some information on the REpower 5M turbine (http://www.repower.de), and then scaling that data so as to correspond in a plausible way to a smaller (3 MW) turbine. Thus, the results provided below are intended to provide an illustration of the expected loads, but cannot be considered final.

The two cases examined were for:

1) Power production at a wind speed of 12 m/s and

2) The turbine with the rotor parked, the blades pitched to reduce loads while subjected to a ten minute averaged wind speed of 35.7 m/s.

Each simulation was 10 minutes long.

6.3.1 Wind Loads on the Sub-Structure during Power Production at 12 m/s

Figure 24 shows the wind speed time series at the rotor hub that was used for the simulation at 12 m/s. In addition, the wind speed used in the simulation varied across the rotor due to turbulence and wind shear (the increase in mean wind speed with height above mean sea level).

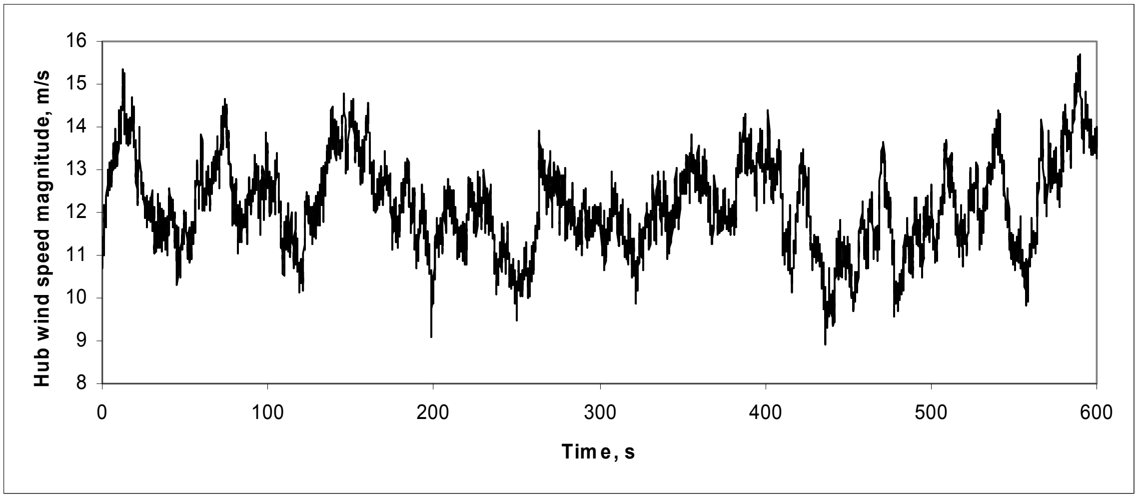


Figure 24 Simulated 12 m/s Wind Speed at Hub

Figures 25 and 26 show the bending moment and the shear force, respectively, at the base of the tower (where the sub-structure begins), due to the loading of the wind in Figure 24. The average bending moment under these conditions is about 27 MNm and the average shear force is about 340 kN. On the other hand, there is quite a bit of variability in the loads. The peak tower base bending moments under these circumstances reach about 35.5 MNm and peak tower base shear forces are close to 450 kN.

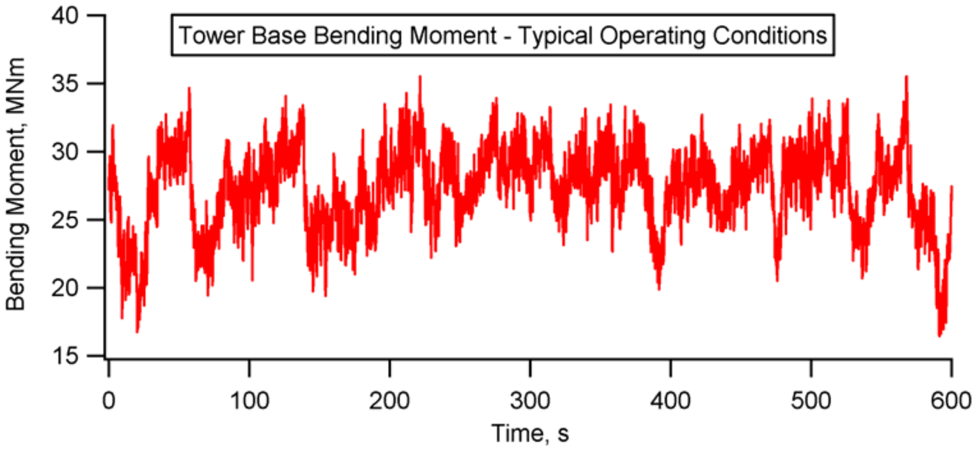


Figure 25 Bending Moment at the Tower Base during Power Production at 12 m/s

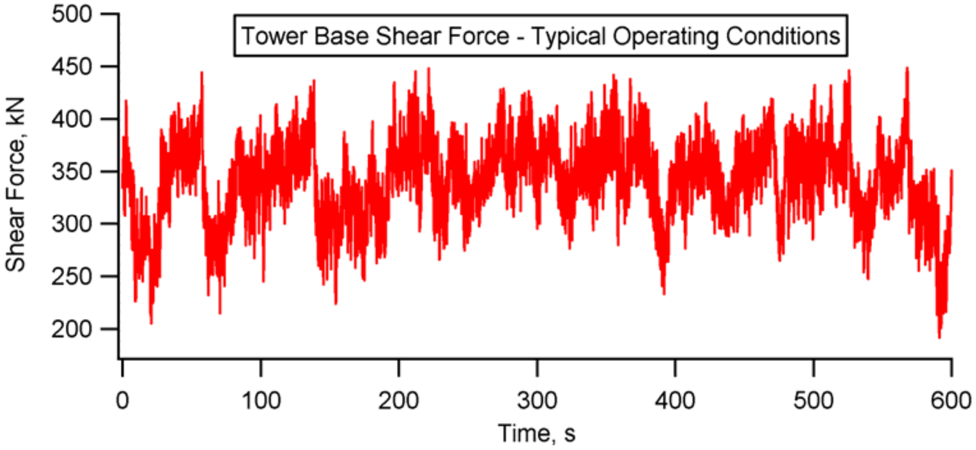


Figure 26 Shear Force at the Tower Base during Power Production at 12 m/s

6.3.2 Wind Loads on the Sub-Structure at Higher Wind Speeds

Figure 27 shows the hub height wind speed time series for a ten minute averaged wind speed of 35.7 m/s. These wind speeds were used in the second simulation.

Figures 28 and 29 show the bending moment and the shear force, respectively, at the base of the tower (where the sub-structure begins), due to the loading of the wind in Figure 27. In this case, average tower base bending moments under parked conditions reach about 2 MNm and average tower base shear forces are less than 30 kN. On the other hand, peak tower base bending moments under parked conditions reach about 4.1 MNm and peak tower base shear forces are about 56 kN. These values are significantly less than the loads during operation at 12 m/s.

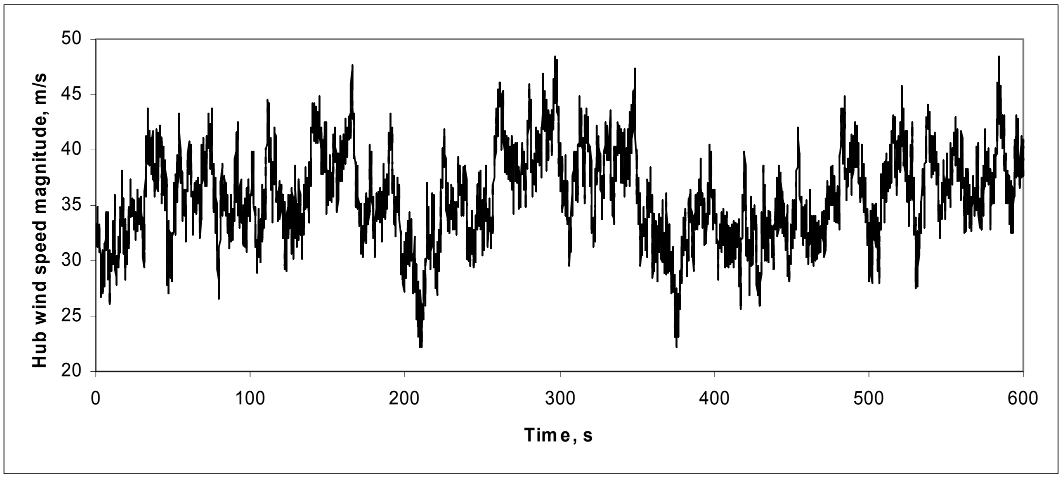


Figure 27 Wind Time Series with Mean of 35.7 m/s

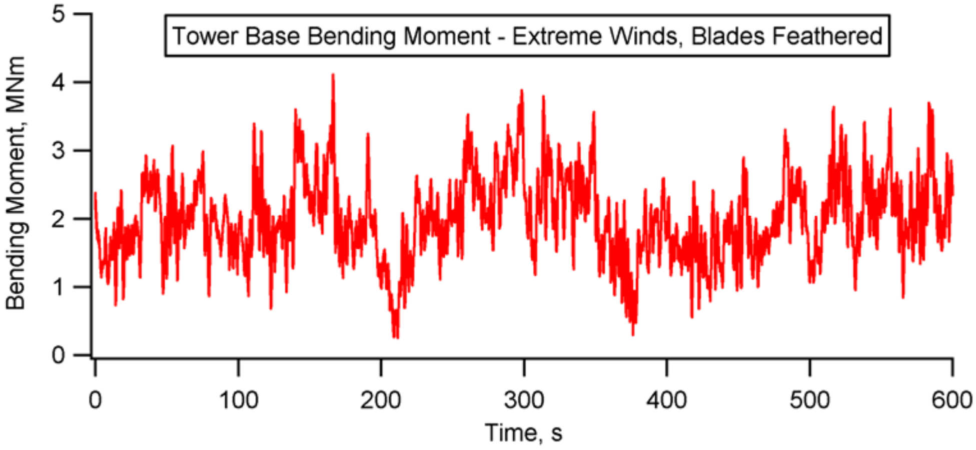


Figure 28 Bending Moment at the Tower Base for 35.7 m/s; Parked Conditions

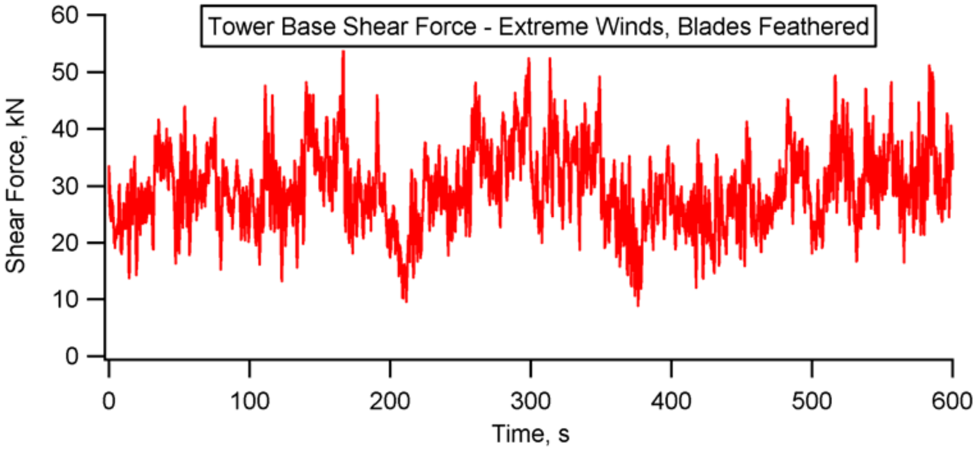


Figure 29 Shear force at the base of the tower for 35.7 m/s parked conditions

6.3.3 Summary of Loads on the Sub-Structure

The loads calculated in the two simulations are summarized in Table 5

Table 5 Summary of Loads on Sub-Structure.

Condition	Tower Base Bending Moment, MNm		Tower Base Shear Force, kN	
	Mean	Max	Mean	Max
Operating, Rated Wind Speed	27.3	35.5	341	449
Parked, High Wind Condition	2.0	4.1	29.6	55.8
Combined structure weight	270 metric tons (~2648 kN)			

A full analysis of all operating conditions, using a model of the wind turbine and support structure that would be used at Hull (and including correct soil conditions), would be required to determine the actual peak loads experienced by the turbine and the total fatigue damage to the structure.

7.0 Environmental Benefits

The environmental benefits investigation has only just begun, so there are no results to report.

8.0 Conclusion

After an extensive period of initial discussions, the detailed feasibility study and permitting stage of the Hull Offshore Wind Project is well underway. Over the course of the next six months, most of the studies that have been envisioned will be completed. The focus after that will be on obtaining all the required permits, securing final approval from the Town to proceed, and making the arrangements to acquire and install the wind turbines.

9.0 Acknowledgments

The authors would like to acknowledge the Town of Hull and the Massachusetts Technology Collaborative for their support of the work described in this paper.

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