Optimizing the Layout of Offshore Wind Energy Systems

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Abstract

Offshore wind energy technology is a reality in Europe and is poised to make a significant contribution to the U.S. energy supply in the near future as well. The layout of an offshore wind farm is a complex problem involving many trade-offs. For example, energy production increases with turbine spacing, as do electrical costs and losses. Energy production also increases with distance from shore, but so do O&M (operations and maintenance), foundation, transmission, and installation costs. Determining which of these factors dominate requires a thorough understanding of the physics behind these trade-offs, can lead to the optimal layout, and helps lower the cost of energy from these farms. This paper presents the results of a study carried out to investigate these trade-offs and to develop a method for optimizing the wind farm layout during the micrositing phase of an offshore wind energy system design. It presents a method for analyzing the cost of energy from offshore wind farms as well as a summary of the development of an offshore wind farm layout optimization tool. In addition to an initial validation of the optimization tool, an example of the use of this tool for the design of an offshore wind farm in Hull, Massachusetts, is also given.

B) Motivation

In the U.S., several offshore wind projects have been proposed, but, at the present time, no offshore wind farms have been constructed. Also, it should be noted that the design conditions for offshore wind systems in the U.S. are somewhat different than those faced by European offshore wind farms (Manwell et al., 2007; Tarp-Johansen et al., 2006). For example, U.S.
coastal water depths are quite varied, ranging from shallow waters off New England to much deeper waters off the West Coast. Proximity to load centers, local opposition, and/or physical constraints imposed by the bathymetry may require some U.S. offshore wind farms to be located in deep water and/or far from land. It is typically assumed that wind farms of this nature are more expensive to construct and operate than those closer to shore and in shallow waters. In general, however, the wind resource improves farther from shore.

An analysis tool for the optimization of an offshore wind farm should therefore contain the following attributes in order to capture offshore wind farm design requirements:

1. Compatible with offshore farms
2. Have the following layout optimization capabilities:
   a) Maximization of energy production
   b) Minimization of cost of energy
   c) Allows physical site constraints
   d) Treats turbine wakes
   e) Includes consideration of collection cables within the model
   f) Allows arbitrary turbine layouts

A detailed literature review (Elkinton, 2007) revealed that a significant amount of research had been conducted in the areas of offshore wind farm component cost modeling, wind farm performance modeling, and placement optimization. Very little work, however, had been done to combine these three areas into micrositing optimization or cost and energy trade-off analysis. For example, Table 1 summarizes the capabilities of four commercial codes for wind farm optimization and how they relate to the above attributes. No available software package met all the desired attributes, and this provides the basis for the work described in this paper.

This paper summarizes the results of a research project intended to investigate the design trade-offs and to develop a method for optimizing the wind farm layout during the micrositing phase of an offshore wind energy system design. The full details of this work are presented in the Ph.D. dissertation of Elkinton (2007). The specific objectives of this work were:

1. The development of a modular analysis tool that gives reasonable estimates of an offshore wind farm’s cost of energy (COE) based on a realistic set of input parameters.
2. The development of a design tool that optimizes the layout of an offshore wind farm such that the COE is minimized.
3. The use of these tools to investigate the influences of site-specific conditions on the COE, trade-offs between energy production and cost, and optimized layout design.

It should be noted that, while the results given later in this paper are for fixed (i.e. non-floating) turbines, the methodology is general and can be applied to fixed or floating technologies.

### Wind Farm Analysis Component Models

The Offshore Wind Farm Layout Optimization (OWFLO) analysis tool is comprised of several mathematical models that estimate the contributions of the major energy and cost components of a particular offshore wind farm to the farm’s COE. The models account for the site-specific conditions that can have a significant impact on the cost of energy. These component models are shown in Figure 2. A note on nomenclature: RNA refers to the Rotor-Nacelle Assembly, which represents the portion of the turbine that is above the tower. O&M is Operations and Maintenance.

The key inputs to the individual analytical models are illustrated in Figure 3.

As shown in Figure 3, the different sub-component modes can be divided into two categories: 1) Energy production and 2) Cost models. A detailed description of each of these cost models is beyond the scope of this paper. However, an overview of the component modeled and some highlights of various component models are given. It should also be noted that these models were intended for use in a life cycle cost model for the offshore wind farm and give preliminary design results that are not intended for the final design of an offshore wind farm. In most cases, the submodels have been validated with data from operating wind farms and, in our initial work, were intended to be within ±25% of the actual values—a range of uncertainty deemed reasonable for the model’s intended use.

#### A) Energy Production Models

1. **Power Production Model**

   For this subcomponent, the analytical tool normally uses an input of the wind...
turbine manufacturer’s power curve data (which represents the conversion between wind speed and electrical power output); alternatively the rotor power may be estimated by using a generic power curve that is scaled with the rotor diameter.

2. Wake Model

The knowledge of wake characteristics in a wind farm can be a significant factor in determining its total power output. Predicting the airflow within a wind farm has been the subject of much investigation and numerous approaches, ranging from empirical and analytical models to complex computational fluid dynamics (CFD) models, have been developed in the past (Manwell et al., 2003). For this work, models that are mathematically describable are most useful, so the wake model suggested by Katic et al. (1986), often called the PARK model, was used.

3. Electrical Losses

Two electrical cable loss models were developed. The first one, a more complex model, is based on transmission line theory and relies on the characteristics of the particular undersea cable to be used (Brakelmann, 2003; Negra et al., 2006). The second is based on an empirical transmission line loss model (Elkinton, 2007).

4. Availability Model

Availability is defined as the percentage of time that the wind farm is able to produce electricity, regardless of whether or not the wind is blowing. According to the European DOWEC study (Hendriks and Zaaljier, 2004), the contribution of the layout to the availability is small; thus a nominal estimate of a 95% availability was assumed.

B) Cost Models

In this model, the levelized production cost (LPC) is used to represent this cost of energy. The LPC is given by

\[ \text{LPC} = \frac{CC}{a \cdot E_a} + \frac{C_{O&M,a}}{E_a} \]

where \( CC \) is the capital cost of the project (or project cost), \( C_{O&M,a} \) is the annual operation and maintenance (O&M) cost, \( a \) is the annuity factor, and \( E_a \) is the annual energy production. Each of the component models contributes either to \( CC \), \( C_{O&M,a} \), or \( E_a \) and, thus, give the analysis tool the ability to estimate the LPC for a given wind farm.

The subcomponent models are needed to estimate the cost of the various offshore wind farm components. They include the rotor-nacelle assembly (RNA), support structure, electrical interconnection, operation and maintenance (O&M), and decommissioning. It should be noted that the cost of installation was included in the cost of the components themselves.

1. Rotor-Nacelle Assembly (RNA) Model

The analysis of this component is based on an empirical model that predicts the RNA cost from the rated power of the wind turbine. In addition, the weight of this component is predicted since it is needed for the cost models for the different parts of the support structure.

2. Support Structure Model

The support structure consists of the tower, sub-structure, and foundation. As described by Elkinton (2007), this is the most complex subcomponent model, and the one with the greatest uncertainty. The tower model used in this work is empirical in nature and is based on the DOWEC project work of Bulder, et al (2000). The support structure submodel is further complicated by the choice between gravity bases, monopiles, or tripods for the tower foundations. The cost models for these designs must also adhere to IEC standards on offshore wind turbine design (currently in committee draft form) (IEC, 2005). Also, the wind and wave loads, as well as the soil bearing capacity at a particular ocean site must be determined for this subcomponent.
model. While floating or other deep water support structures were not explored here, they are envisioned as a future and natural extension of this work.

3. Electrical Interconnection Models

The electrical interconnection system collects the electrical power within the farm and transmits it to the shore and the power grid. This subcomponent model separates the collection and transmission functions and models them using medium (MVAC) and high voltage AC cables (HVAC). In the future it is expected that DC cables will become economically competitive and will need to be modeled for this subcomponent. The cost modeling of this component is carried out in conjunction with an electrical loss model and is based on empirical relations from existing offshore wind farms. For example, the cost model for the HVAC cable system is based on the work of Ackerman, et al. (2005).

4. Operation and Maintenance (O&M) Model

Here a choice of two O&M models is used for this subcomponent. One is based on a fixed percentage of the capital cost, and the second one is based on a fixed cost per unit of energy.

5. Decommissioning Model

The decommissioning model used here is empirical and is based on the results of two recent reports on this subject (Climate Change Capital, 2006; Pearson, 2001).

Wind Farm Analysis

For this phase of the work the individual component models were combined and implemented to calculate the levelized production cost (LPC) of the entire offshore wind farm. Thus, one purpose of this integration is to estimate the LPC for a specific wind farm and layout. As will be discussed in the next section, another purpose of this tool is its use for the evaluation of many different layouts with the minimum LPC.

The overall analysis process is shown in Figure 4 and, as described by Elkinton (2007), includes a methodology for an annual energy production estimate using wind data from the site and wake effects associated with the particular wind farm layout under analysis (Lackner and Elkinton, 2007).

A calculation of the LPC is made possible by use of the OWFLO analysis tool, which is a software program written to facilitate the passing of data to and from the component models. The tool gathers data such as the wind farm layout, wind data, simple economic parameters, and configurations for various component models from the user using a graphical user interface (GUI). Using these inputs, the analysis tool then estimates the mean power, annual energy production, and cost for each of the turbines, as well as the total capital cost, energy production, and LPC for the farm.

In order to validate the net result of all of the component models (costs, energy production, and LPC) an analysis of the Middelgrunden offshore wind farm was made using the OWFLO Analysis Tool. The Middelgrunden farm is located 3 km outside Copenhagen harbor in Denmark. It consists of 20 Siemens (formerly Bonus) 2 MW turbines that are installed on gravity base foundations in 3-6 m of water. Wind and power data have been obtained from the Middelgrunden Wind Energy Cooperative (Larsen, 2005), the owner of the southern 10 turbines. Cost data for these turbines are available in Larsen et al. (2005) and from the project website (SEAS DENMARK, 2006). The availability of these economic and production data made Middelgrunden an ideal farm with which to evaluate the OWFLO models.

FIGURE 4

Flowchart for LPC Calculation.
Table 2 gives a summary of the validation results. One 12-month set of wind and power data, from October 16, 2001 to October 16, 2002, was used in this comparison. During this period, Middelgrunden produced 100.2 GWh and the OWFLO Analysis Tool estimated 100.9 GWh. The budgeted LPC was approximately 4.7 ¢/kWh, based on the 89 GWh annual production guaranteed by the manufacturer. When the LPC was calculated using the actual energy production and the actual capital and O&M costs, the result was 4.2 ¢/kWh. As can be seen, most of the components costs were close to our target goal, but a major discrepancy occurred in the cost of the rotor-nacelle assembly (RNA). The estimated value may be high due to recent increases in turbine costs, and if a RNA cost of $26.7 million (actual RNA cost) were used in the estimation, the LPC becomes 3.8 ¢/kWh, which is within 10% of the actual value.

It should be noted that the actual costs of any wind farm, whether onshore or offshore, depend a great deal on the turbine market. The costs listed in Table 2 above were consistent (if slightly low) with the costs in the year 2001, but would be considered out-of-date according to the market at the time this paper was written. Today's currently expected costs are significantly higher. Tying the cost models to the market trends is one of the challenges faced during this work.

Wind Farm Optimization

The problem of optimizing wind farm layouts falls into the class of problems called combinatorial optimization. Several papers and books have been written about this

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**TABLE 2**

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>Actual</th>
<th>OWFLO Estimation</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual energy production</td>
<td>100.2 GWh</td>
<td>105.0 GWh</td>
<td>5%</td>
</tr>
<tr>
<td>(89 GWh guaranteed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity factor</td>
<td>28.6 %</td>
<td>30.0 %</td>
<td>5%</td>
</tr>
<tr>
<td>(25.4 guaranteed)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine</td>
<td>$39.6 million</td>
<td>$59.7 million</td>
<td>51%</td>
</tr>
<tr>
<td>RNAs</td>
<td>$26.7 million b</td>
<td>$46.8 million</td>
<td>75%</td>
</tr>
<tr>
<td>Support structures</td>
<td>$12.9 million</td>
<td>$12.9 million</td>
<td>0%</td>
</tr>
<tr>
<td>Electrical collection system</td>
<td>$4.5 million</td>
<td>$1.2 million</td>
<td>-73%</td>
</tr>
<tr>
<td>Other (e.g. decommissioning)</td>
<td>$4.4 million</td>
<td>$4.0 million</td>
<td>-9%</td>
</tr>
<tr>
<td>Total capital cost</td>
<td>$48.5 million</td>
<td>$65.0 million</td>
<td>34%</td>
</tr>
<tr>
<td>Annual O&amp;M cost</td>
<td>$801,000</td>
<td>$1.5 million</td>
<td>87%</td>
</tr>
<tr>
<td>Installed cost</td>
<td>$1145 / kW</td>
<td>$1625 / kW</td>
<td>42%</td>
</tr>
<tr>
<td>Levelized Production Cost</td>
<td>4.2 ¢/kWh c</td>
<td>5.4 ¢/kWh</td>
<td>29%</td>
</tr>
<tr>
<td>(4.8 ¢/kWh budgeted)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Actual cost figures converted from Euros assuming $1 = 1€ in 2001. 
  * Cost of the tower included in actual RNA cost.
  * Estimate based on actual project cost and energy production for the year of data analyzed.
class of problem, including multiple papers related to wind farm layout. All of these papers have been concerned with onshore wind farm design, but provide good starting places and sources of comparison for this investigation of offshore wind farm layouts (Mosetti et al., 1994; Ozturk and Norman, 2004; Grady et al., 2005).

The two keys to successful optimization are the choice of an optimization algorithm that is appropriate for the problem, and the identification of the correct objective function. For this work, the objective function that was selected was the minimization of the LPC, along with a combination of two optimization algorithms: the genetic algorithm and the greedy heuristic algorithm (Elkinton, 2007; Elkinton et al., 2008). The flow charts for both of these algorithms are given in Figures 5 and 6. The principle behind the genetic algorithm is the Darwinian concept of natural selection that is applied to an iterative process until the optimization criteria are satisfied (Elkinton, 2007). The greedy heuristic algorithm begins with an initial guess or seed. This seed undergoes a series of modifications (add, remove, or move) that result in additional potential solution guesses. For both these choices, in order for the algorithm to perform most efficiently, several parameters in each algorithm had to be tuned (see Elkinton, 2007 for the tuned value parameters).

Following a detailed investigation of the uses of both these algorithms for offshore wind farm layout optimization (Elkinton, 2007; Elkinton et al., 2008), it was concluded that a series combination of the genetic and greedy heuristic algorithms resulted in the best results. In this case the genetic algorithm provided the initial seed for the greedy heuristic algorithm.

**Optimization Case Study**

**Example**

**A) Location:**

The town of Hull, Massachusetts, is located 13 km east-southeast of Boston at the southern end of the entrance to Boston Harbor (see Figure 7). The town currently owns two utility-scale onshore wind turbines and has started the process of developing a small offshore wind farm within town waters. This project provides an opportunity to test the optimization algorithms and modeling software in a real-world setting. When the Hull Municipal Light Board voted to pursue the installation of an offshore wind farm, they decided that the farm should contain 4 turbines. Therefore, all of the energy and economic estimations presented here are based on the assumption that four 3 MW turbines are to be installed.

**B) Site Description**

The initial wind data for this study were obtained through a measure-correlate-predict (MCP) process (Rogers et al., 2006). Short-term data were measured at a height of 61 m above the ground using cup anemometers on a radio tower near the coast of Hull. These data were combined with 4 years of data measured at a met tower located on Thompson Island, located in Boston Harbor, approximately 12 km (7.5 miles) west-northwest of the town of Hull, Massachusetts, showing Hull’s proximity to Boston, the offshore town boundaries, the locations of the two onshore turbines in Hull, and the location of the radio tower where wind data were measured. The wind data were translated from the radio tower to the coast by multiplying the data by the ratio of the mean speeds at the two locations (ratio = 1.01). The data were also extrapolated to the 80 m proposed hub height using the power law exponent derived from the 50 m and 70 m wind map data. This exponent, \( \alpha = 0.174 \), has been chosen over the exponent measured at the radio tower (\( \alpha = 0.182 \)) in order to obtain a conservative energy estimate. The estimated mean wind speed at 80 m at the Thompson Island site location is 7.1 m/s. These translated and extrapolated offshore wind data have been used in the optimization analyses summarized here.

The wind at this site is characterized by the wind speed histogram and wind rose shown in Figure 8. As the wind rose shows, the large majority of the wind comes from the west and southwest. The overall Weibull \( c \) and \( k \) parameters at 80 m at the site are 8.0 m/s and 2.2, respectively.

The wind map was used again to determine a functional relationship between the wind speed and the distance from shore, \( x \), measured in kilometers:

\[
U(x) = U_{\infty} \left[ -0.17 \exp \left( \frac{-x}{3.21} \right) + 1.17 \right]
\]

The seafloor off Hull has been characterized as mostly boulder and cobble, with a well-defined corridor of sand (Ackerman...
Acoustic sub-bottom profiling was undertaken (CR Environmental, 2007) to determine the depth of the bedrock at the site. Soil borings are planned for late spring of 2008. An investigation of the wave conditions at the site is currently underway, but initial estimates suggest that the 50-year reduced wave height (extreme wave height with a return period of 50 years) is 6.8 m and the characteristic wave period is 9.9 s.

C) Optimization Study Results
An initial analysis considering Hull’s total offshore area showed that the greatest energy production would be achieved farthest from shore. At 7.4 km (4 nautical miles) from the coast, the estimated mean wind speed is 8.1 m/s at 80 m, compared to 7.6 m/s at 1.9 km (1 nautical mile) from the coast. For four 3 MW turbines, the estimated energy yield at 7.4 km is 36 GWh, compared with 32 GWh at 1.9 km from the coast. The wind, energy, and initial cost estimations are summarized in Table 3 and the optimized layout for the Hull offshore wind farm is shown in Figure 9. It should be noted that the cost estimates are preliminary and were developed for comparative purposes.

According to the results of this work, the wind speed off Hull increases with distance from shore as expected, indicating that the highest energy production is obtained at the far edge of the town boundary. The results also show, however, that the capital cost increases farther from shore. The optimization algorithms have been used to balance these two competing factors. The optimal layout shows that, for the case of Hull, the increased cost of a farm farther from shore outweighs the benefits of higher energy production.

It should be noted that an important lesson was learned during the preliminary optimization of the Hull site. That is, initially the total area with Hull’s boundaries was too large for the optimization tool to give consistent results. The most efficient methodology was to run the optimization tool several times over the total area to identify a smaller area in which to search further. The search was then restricted to this smaller area and the process was repeated. The solution described here was the result of one such iteration.

The results also indicate that, for this case, the cost per kWh is relatively insensitive to the exact nature of the layout, assuming that a reasonable spacing (in this case at least 2 rotor diameters) is maintained between the turbines. This allows flexibility in determining their exact location. For example, aesthetics, fisheries, and archaeology factors can be considered without greatly affecting the cost of delivered energy.

Summary and Conclusions
This work has resulted in the development of an economic cost model for offshore wind farms and an optimization tool for minimizing the cost of energy from offshore wind systems. This tool is useful in investigating the cost and energy trade-offs associated with the layout optimization for an offshore wind farm. These include the

### Table 3
Summary of analysis results for the proposed Hull offshore wind farm consisting of four 3 MW turbines.

<table>
<thead>
<tr>
<th>Location</th>
<th>1.9 km from shore</th>
<th>7.4 km from shore</th>
<th>Optimal solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean hub-height wind speed [m/s]</td>
<td>7.6</td>
<td>8.1</td>
<td>7.7</td>
</tr>
<tr>
<td>Annual energy production [GWh]</td>
<td>32</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>Capacity factor [%]</td>
<td>30</td>
<td>34</td>
<td>31</td>
</tr>
<tr>
<td>Support structure</td>
<td>Monopiles</td>
<td>Gravity bases</td>
<td>Monopiles</td>
</tr>
<tr>
<td>System cost [$ million]</td>
<td>22</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>Levelized production cost [¢/kWh]</td>
<td>7.6</td>
<td>7.9</td>
<td>7.6</td>
</tr>
</tbody>
</table>
added cost vs. added output due to increases in distance from shore, hub height, etc. As has been demonstrated here, this tool can also be used during initial design studies to identify the most economic portions of the farm area and to highlight the important features of a given site design.

The data available for validation have been few and of less than optimal quality. Perhaps the most important next step is an upgrade and thorough validation of the component models using, if possible, data from actual projects.

Several opportunities for future research are suggested by this work. These include improvements to component models, enhancements of optimization strategies, and additional options that would help the OWFLO tools to be more broadly applicable—for example floating support structure models could be added. Several of the component models used for the sensitivity analysis for Hull showed to be significant to the LPC (availability, RNA cost, and O&M cost) have been necessarily simplified for this project. The development of more rigorous models would decrease the overall uncertainty of the LPC analysis and layout optimization.

References


Hendriks, H.B. and Zaaijer, M.B. 2004. DOWEC: Executive Summary of the Public Research Activities. ECN, Petten, NL.


