OFFSHORE WIND FARM LAYOUT OPTIMIZATION (OWFLO) PROJECT: AN INTRODUCTION

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ABSTRACT

Optimizing the layout of an offshore wind farm presents a significant engineering challenge. Most of the optimization literature to date has focused on land-based wind farms, rather than on offshore farms. The conventional method used to lay out a wind farm combines a turbine cost model and a wake model in conjunction with an optimization routine. In offshore environments, however, factors such as operation and maintenance (O&M) and availability also play significant roles in the design of a wind farm. To better account for these and the other critical factors that distinguish offshore wind farms from their onshore counterparts, the Offshore Wind Farm Layout Optimization (OWFLO) project was launched in 2004. The objective is to develop an analysis tool that unites offshore turbine micrositing criteria with efficient optimization algorithms. The project combines wake and component cost models, but also includes O&M, availability, and electrical interconnection models. When integrated within an appropriate optimization routine, these "sub-models" will work together to better reflect the real-world conditions and constraints unique to individual offshore sites. The OWFLO project will consider several optimization algorithms—including heuristic and genetic methods—to minimize the cost of energy while maximizing the energy production of the wind farm.

This paper summarizes the results from the first year of this on-going project. The development of the component models and analysis software is discussed in detail and some initial results are compared with existing wind farms. A summary of the current and future phases of the project is also presented.

Keywords: offshore wind energy, optimization, micrositing, cost model, wake model

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1 INTRODUCTION

The University of Massachusetts Amherst, MIT, and the Woods Hole Oceanographic Institute have established an offshore wind energy collaborative. Funded by the Massachusetts Technology Collaborative (MTC), GE Energy, and the US Dept. of Energy (US DOE), this collaborative is addressing some of the most significant research questions in the realm of offshore wind energy in the US. This project represents a part of this research.

In the US, offshore wind farms may eventually exist primarily in deep water and many kilometers from shore. Due to local opposition as well as physical constraints imposed by the bathymetry, deeper water away from land looks like an appealing option. It is well understood, however, that farms of this nature are more expensive than those closer to shore

and in shallow waters. In order to begin to quantify the magnitude of this cost difference, a method of modeling the costs of wind farms in varying water depths and at varying distances from shore is needed. With this type of model, the economic constraints of offshore wind energy can be better understood. This project seeks to provide this economic model.

A note on nomenclature. This paper will make every effort to follow the naming convention being finalized by the offshore wind working group of the International Electrotechnical Commission. Figure 1 is given here for reference.

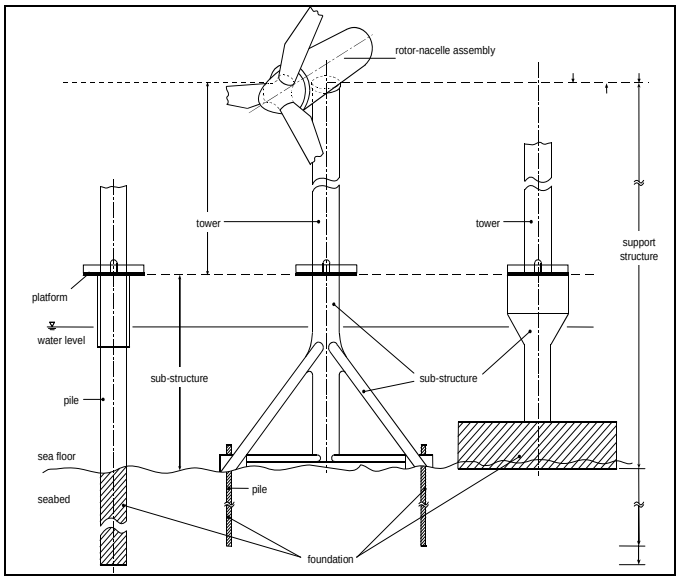

Figure 1 - Turbine component nomenclature [18]

1.1 Project objective

The goal of the Offshore Wind Farm Layout Optimization (OWFLO) project is the development of a software tool that will streamline the micrositing process. By combining energy models, cost models for the major wind farm components, and an optimization algorithm, the cost of energy (COE) can be minimized while accounting for real-world constraints. The following wind farm component cost models are included:

- turbine cost
- support structure cost
- electrical interconnection cost
- operation and maintenance (O&M) cost
- installation and decommissioning costs

The following energy models are also used:

- single turbine power production
- turbine wake
- electrical line loss
- availability

The OWFLO tool is being designed to perform two functions: layout analysis and layout optimization. By using the optimization routine, the user will get the optimum layout. Then, if the layout is adjusted for aesthetic, practical, or other reasons, the analysis routine will

show how much energy is lost through these adjustments. This overall concept is illustrated in Figure 2.

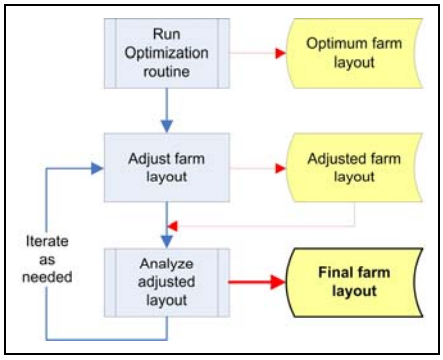

Figure 2 - The optimization and analysis routines will be used together to refine a wind farm layout

The analysis feature is being developed first. With it, the user will be able to evaluate the costs and energy production of a predefined layout. The cost and energy models listed above will be applied to the specified layout, and the software will report the expected overall costs and energy production.

The optimization capabilities will allow the software to search for the layout configuration with the lowest COE and/or the greatest energy production based on the results of the models. This part of the project is scheduled to be developed during the coming year.

1.2 Background

Determining the optimum layout for an offshore wind farm involves many tradeoffs. For example, the further the turbines are from shore, the higher the wind speeds and the greater the energy production. However, the electrical cable costs and O&M costs increase significantly with distance from shore, so the costs also increase. Another example is the spacing of the turbines. Placing turbines close together reduces the electrical cable costs. By doing so, however, the total energy decreases and the turbulence increases which decreases the component overall lifetime. There is a need for efficient ways to find these balances and this project is an effort to provide one.

Several previous studies, which have direct relevance to OWFLO project, are available in the literature. These range from studies of scaling relations for various turbine components to non-wind-related studies in placement optimization. The most relevant ones are summarized here.

1.2.1 Wind farm costs

Several major European projects have looked at the scaling of turbine components. One was the Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS) study [12]. The Opti-OWECS study investigated the state of the art of offshore wind turbines from 1996 to 1997 and endeavored to determine methods by which to lower the COE from offshore wind farms over the following 10 years. The Opti-OWECS study covered, in varying detail, the economics of offshore turbines, support structures, electrical interconnection, installation, siting, layout, and O&M options. Starting with the then (1997) state of the art, new designs and strategies were projected through the

following 10 years. The Opti-OWECS study was regarded as the definitive work on the subject of offshore turbines when it was published. It contains some very detailed and specific cost information that has direct application in the OWFLO project.

The cost components upon which the OWFLO project is concentrated are those identified by the Opti-OWECS and OWECOP (Offshore Wind Energy – Cost and Potential) projects (Table 1). The OWECOP project is currently underway at ECN and is focused on the development of software to model offshore wind farm costs in a given geographic area. The OWECOP software combines simplified engineering models (using an Excel spreadsheet) with Geographic Information Systems (GIS) [11]. It is similar in concept to the OWFLO project, but the OWFLO project considers at micrositing issues whereas the OWECOP project looks at broader wind farm siting issues.

Table 1 - Major cost components of an offshore wind farm

Component	% of energy cost (Opti-OWECS)	% of Installed cost (OWECOP)
Turbines and tower	34	25
Sub-structure and foundation	24	11
O&M	23	17
Electrical interconnection	15	17
Installation and decommissioning	included in above	18
Other	4	12

The Dutch Offshore Wind Energy Converter (DOWEC) project [8] looked at ways of improving offshore wind turbine design and increasing their cost-effectiveness. The project looked to identify ways to design and build better, more reliable large turbines (5-6 MW) for large (100s of MW) farms because. The DOWEC study, conducted from 1997 - 2003, examined electrical, O&M, support structure, and turbine costs as well as turbine wakes. The scaling relationships given in the reports have been adapted for use in the OWFLO project.

It should be noted that there are commercial products which are currently used to lay out wind farms, including WindFarm (ReSoft, UK), WindFarmer (Garrad Hassan, UK), and WindPRO (EMD, Denmark). WindPRO, for example, was used in the SEAWIND report [6]. Their latest report gave several relations for wind farm costs, but stated that further work on the optimization and layout capabilities was required.

1.2.2 Turbine wakes

Considerable effort has gone into understanding turbine wakes in offshore environments. A good example of this is the ENDOW project [2]. The primary goal of the Efficient Development of Offshore Windfarms (ENDOW) project was to link boundary-layer and turbine wake models to better determine the wind shear and turbulence profiles inside large offshore wind farms. The ENDOW project was headed by Risoe and included model from ten organizations in Europe. During the course of the project, improvements to each of the wake models were identified and implemented.

1.2.3 Placement optimization

When the analysis part of the OWFLO software has been completed and validated, the optimization routine will be developed. Typically, gradient ("hill-climbing") optimization methods are able to find local maxima or minima, but not necessarily the overall maximum or minimum. In addition, analyzing each possibility becomes computationally intensive. For example, if each cell in the farm grid can have 2 possible states—contains a turbine or does not contain a turbine—then even for a small 10 x 10 grid, there are $2^{100} \approx 10^{30}$ possible cases to evaluate. None of the wind farm optimization papers reviewed used gradient methods.

Instead, two alternative approaches have been suggested: heuristic and genetic optimization algorithms. Each of these algorithms uses an element of randomness to dislodge the solution from the local minima in an effort to find the overall minimum. These methods will be the primary focus when the optimization routine is developed. The applicability to wind energy of each of these methods has been investigated and is available in the literature. See the study from Hawaii Pacific University and the University of Pittsburgh [17] for information of a heuristic algorithm. Information on the use of genetic algorithms can be found in [14,15,7].

2 PROJECT DESCRIPTION AND METHODOLOGY

2.1 Project schedule

The first phase of the project analyzes wind farms with fixed turbines in shallow water. The focus of this phase is on the development of the component models. Simple versions of the models are being used, starting with models discussed in the literature. This first phase will have been completed by September 2005.

During the second phase, the optimization routine will be added. From the literature, the two most applicable optimization routines are the heuristic and genetic algorithms. These will both be considered for this project. Additional emphasis will be placed on the development of an intuitive, graphical user interface.

The focus of the third phase of the project will be to use the OWFLO tool to investigate deep-water installations. The objective for this phase is to begin to quantify site parameters required in order to develop economically-viable deep-water wind farms. During this phase, the existing models will be refined and more sophisticated models will be added to improve the accuracy of the results. In addition, the software tool will be taught to optimize wind farms in deep water. The major change from the shallow water conditions is expected to be the support structure model. This final phase of the project should be complete by September 2006.

2.2 Software architecture

The structure of the OWFLO software is modular (Figure 3). The main benefit of a modular structure is flexibility: as additional or more robust models are developed, they can be added without requiring major revision of the code. For example, if additional wake models are added, the modular structure will allow the user to select the wake model they wish to use. The expected inputs and outputs have been identified during the literature search, so adding a new model only changes the way the outputs are calculated.

One of the objectives of the optimization is the minimization of the COE. As shown in Figure 4, the COE is comprised of two essentially independent functions: the cost of the system (the numerator) and the energy the system produces (the denominator). Furthermore, the cost function is made up of several component costs which are also independent. If, in time, additional factors are determined to contribute to the system cost, they can be added to the numerator without affecting the other components or models.

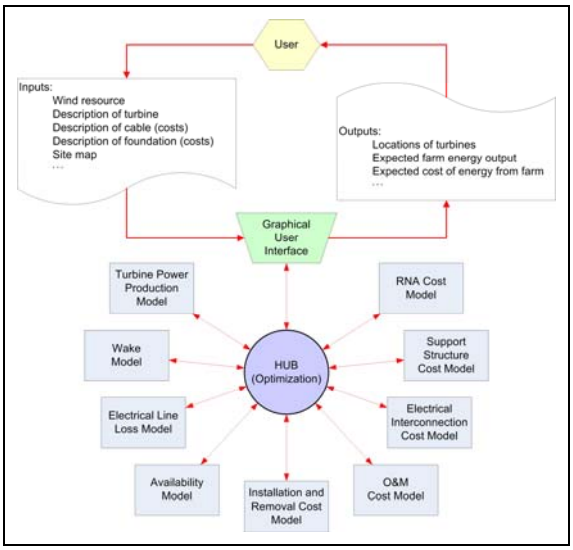

Figure 3 - Modular structure of OWFLO software

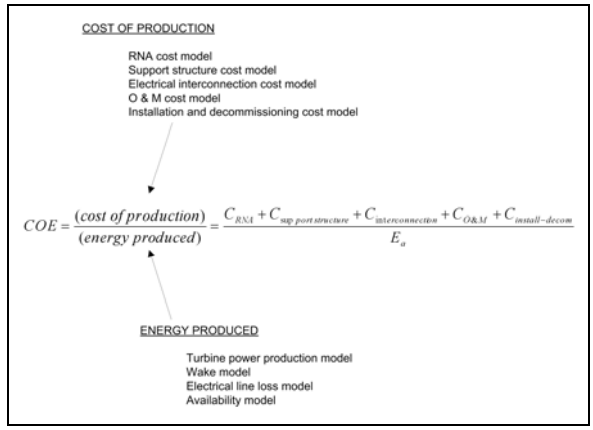

Figure 4 - Cost of energy (COE) function

Some phenomena affect both the costs and the energy production. The electrical interconnection, for example, consists of cables which have a cost. At the same time, however, energy is lost during transmission through these cables. In order to keep the functions in the numerator and denominator separate, this phenomenon is treated using two models, the electrical interconnection cost model and the transmission loss model. Other physical phenomena such as O&M and availability are separated in a similar manner.

2.3 Component models

At the time this paper was written, a wake model, an O&M cost model, and cost models for gravity base and monopile foundations had been either chosen or developed. These first models are simple but give reasonably realistic results. During the second phase of the project, these models will be refined. Installation costs are still under investigation.

The inputs to the component models include the following parameter:

- RNA mass (either modeled or from)
- rotor diameter
- rated power
- hub height
- thrust and power coefficients
- time series of wind speed and direction
- water depth
- distance to shore
- soil bearing capacity

The first 4 parameters can either be modeled or come from manufacturers' specifications. For the purposes of the initial phase of the project, the latter option has been chosen.

2.3.1 Support structure cost

As shown in Figure 1, the support structure consists of the tower, sub-structure, and foundation. For gravity base and monopile structures, these components are modeled using algorithms based on several works [3,16,21,4]. These algorithms use characteristics of the RNA (e.g. mass, hub height, and rotor diameter) and soil properties as inputs and return the masses, costs, and dimensions of the components. Examples of results using these models are given below.

The support structure models currently do not take wave height or breaking waves into account. These factors are important in foundation design and will be included in future revisions of the models.

2.3.2 O&M cost

No complete mathematical model of offshore wind farm O&M costs has been found in the literature. Many studies have investigated availability, component failure, and maintenance strategies. See, for example, [20,5]. Estimating the cost of O&M remains, however, a complicated process. Until a mathematical model capable of dealing with this complexity has been developed, a very simplified model will be used instead. The simplest model of the annual O&M costs is a fixed percentage of the capital cost. Several of these percentages are discussed in the literature. Based on the Opti-OWECS report [13], an annual O&M cost equal to 2% of the capital cost is used.

2.3.3 Wake model

Considerable research has gone into understanding the wind flow within wind farms, both onshore and offshore. Projects like ENDOW highlight the fact that there are several different approaches to modeling this flow, from empirical and analytical models to complex CFD models. For the OWFLO project, models that are mathematically describable are more useful, so the wake model developed in [10], which has been cited in many simple turbine wake studies, will be used.

$$Deficit = \left(1 - \frac{U}{U_0}\right) = \frac{2a}{\left(1 + k\frac{x}{R}\right)^2} \tag{1}$$

Here, U is the wind speed of interest, U_0 is the unaffected wind speed, a is the axial induction factor, k is the wake spreading constant proposed in [15], x is the distance downstream, and R is the rotor radius.

The wake calculation starts by determining a wake for a single turbine which spreads linearly downstream and decays according to a wake decay coefficient. In this model, the wind speed within the wake is assumed to be constant in cross-section because the primary goal is to model the energy deficit in the wake, not the actual wind speed. It should be noted that by assuming a linearly spreading wake, the non-linear near-wake region is ignored, making the model only applicable to distances greater than approximately 4 rotor diameters downstream.

3 INITIAL RESULTS / ANALYSIS

To check the accuracy of the support structure models, parameters from 3 existing wind farms were modeled. The actual and model values are compared in tables below.

The Horns Rev farm uses monopiles for its 80 Vestas 2 MW turbines (80 m rotor, 70 m hub height). Monopiles were also used at Arklow Bank for the 7 GE Energy 3.6 MW turbines (104 m rotor, 74 m hub height). Middelgrunden consists of 20 Bonus 2 MW turbines (76 m rotor, 64 m hub height) on gravity base foundations. Information about the farms is available from [9,1,19].

Table 2 - Horns Rev (monopiles)

Parameter	Actual	Model	Error
Tower top dia. (m)		2.6	
Tower base dia. (m)	4	4.6	15%
Tower mass (1000 kg)	160	118	-26%
Tower cost (1000 $)		177	
Pile dia. (m)	4	4.6	15%
Pile mass (1000 kg)	200	192	-4%
Pile cost (1000 $)		432	
Pile embedment (m)	25	21.6	-14%
Pile thickness (m)	0.05	0.055	10%

Table 3 - Arklow Bank (monopiles)

Parameter	Actual	Model	Error
Tower top dia. (m)	3	3.1	3%
Tower base dia. (m)	5	5.2	4%
Tower mass (1000 kg)	160	179	12%
Tower cost (1000 $)		269	
Pile dia. (m)	5	5.2	4%
Pile mass (1000 kg)		282	
Pile cost (1000 $)		635	
Pile embedment (m)	30	32.9	10%
Pile thickness (m)		0.062	

Table 4 – Middelgrunden (gravity bases)

Parameter	Actual	Model	Error
Tower top dia. (m)		2.5	
Tower base dia. (m)		4.3	
Tower mass (1000 kg)	85	102	20%
Tower cost (1000 $)		152	
Foundation dia. (m)	17	17.6	4%
Base mass (1000 kg)	1652	1790	8%
Base cost (1000 $)	475	502	6%

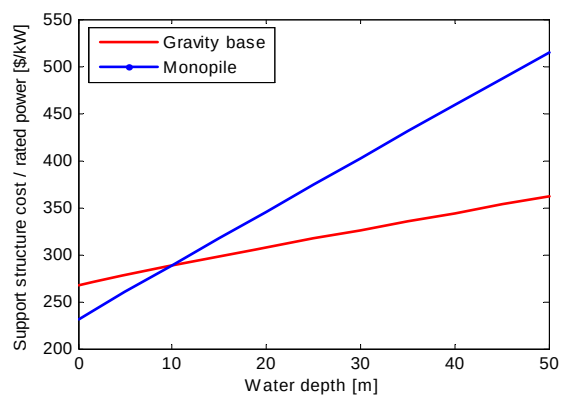

Figure 5 - Cost of the support structure normalized by the rated power.

The models are also useful for studying trends. An interesting example of this is the change in foundation cost with water depth. Figure 5 shows the costs of support structures (including the tower) designed to carry a GE Energy 3.6 MW turbine. For the sake of generality, the costs have been normalized by the rated power of the turbine. The costs of the gravity base have been calculated assuming that it is installed on glacial till (as is the case at Middelgrunden) and the monopile costs assume sand (similar to Arklow Bank).

4 CONCLUSIONS

From the work completed during this first phase of the OWFLO project, a number of conclusions can be drawn. First, there is a perceived need for software that can optimize an

offshore wind farm layout based on COE criteria. This software will be particularly useful as developers look at sites farther from shore and in deeper waters.

Simple cost models exist in the literature for some of the most expensive components of an offshore wind farm. Support structure, O&M, and wake models have been discussed and results of cost models for gravity base and monopile support structures have been given.

Estimated parameter values for gravity base and monopile support structure models were compared to those from the Middelgrunden, Horns Rev, and Arklow Bank wind farms. The model was shown to give foundation parameters to within 10-15%. The tower mass model, in particular, could use improvement.

5 FUTURE WORK

At the time this paper was written, the following Phase 1 tasks remained to be completed:

- Develop a cost model for electrical costs within the farm and for the transmission to land.
- Finalize the simple models for availability and electrical losses.
- Incorporate the wake model (which has already been chosen).

6 ACKNOWLEDGEMENTS

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