

Offshore Wind Farm Layout Optimization (OWFLO)

Project: Preliminary Results

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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. Typically, energy production is the metric by which a candidate layout is evaluated. The Offshore Wind Farm Layout Optimization (OWFLO) project instead uses the levelized production cost as the metric in order to account for the significant roles factors such as support structure cost and operation and maintenance (O&M) play in the design of an offshore wind farm.

The objective of the project is to pinpoint the major economic hurdles present for offshore wind farm developers by creating an analysis tool that unites offshore turbine micro-siting criteria with efficient optimization algorithms. This tool will then be used to evaluate the effects of factors such as distance from shore and water depth on the economic feasibility of offshore wind energy.

The project combines an energy production model—taking into account wake effects, electrical line losses, and turbine availability—with offshore wind farm component cost models. The components modeled include the rotor-nacelle assembly, support structure, electrical interconnection, as well as O&M, installation, and decommissioning costs. The models account for the key cost drivers, which include turbine size and rating, water depth, distance from shore, soil type, and wind and wave conditions. When integrated within an appropriate optimization routine, these component models work together to better reflect the real-world conditions and constraints unique to individual offshore sites. The OWFLO project considers several optimization algorithms—including heuristic and genetic methods—to minimize the cost of energy while maximizing the energy production of the wind farm. Particular attention has been paid to the results of recent European studies, including the ENDOW and DOWEC projects.

This paper summarizes the initial results from this project. A comparison of model results and data from the Middelgrunden offshore wind farm is presented. The overall energy and cost of energy estimations compare well with the real data, but further improvements to the models are planned. A summary of the on-going and future phases of the project is also presented.

Nomenclature

| | | |
|-------|--------------------------------------------|----------|
| a | = annuity factor | |
| b | = axial induction factor | |
| C_c | = capital cost of wind farm | (\$) |
| C_y | = annual costs associated with a wind farm | (\$) |
| E_y | = annual energy production | (kWh) |
| k | = wake spreading coefficient | |
| LPC | = levelized production cost | (\$/kWh) |
| R | = radius of rotor | (m) |

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|-------|---|---------------------------------|-------|
| U | = | wind speed | (m/s) |
| U_0 | = | free-stream wind speed | (m/s) |
| x | = | distance down stream from rotor | (m) |
| z_0 | = | surface roughness length | (m) |
| z_H | = | turbine hub height | (m) |

I. Introduction

The University of Massachusetts Amherst, Massachusetts Institute of Technology, 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 paper describes the status of one of these projects.

In many parts of the US, offshore wind farms may be installed 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 could be an appealing alternative to coastal locations. 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 latest naming convention being finalized by the offshore wind working group of the International Electrotechnical Commission¹, as shown in Figure 1.

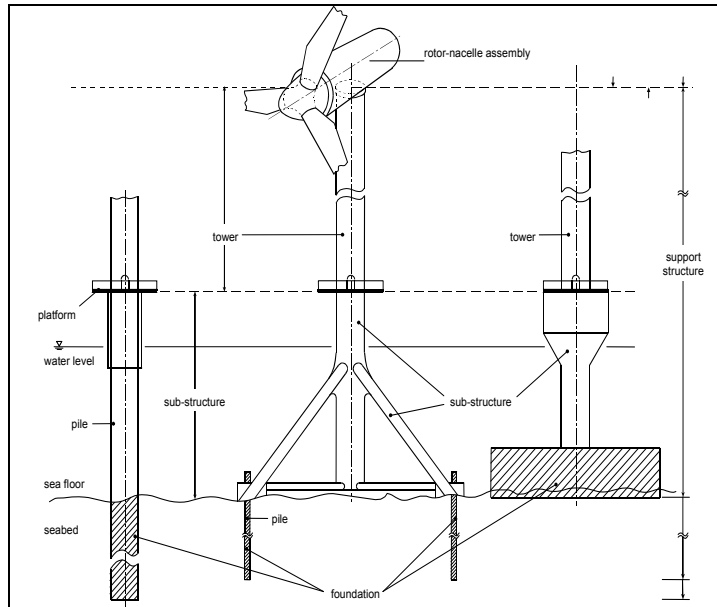


Figure 1. Turbine component nomenclature¹

II. Objectives and Background

A. Project objectives

The primary objective of the Offshore Wind Farm Layout Optimization (OWFLO) project is the development of a software tool that can be used to model and understand the cost and energy trade-offs inherent to the micro-siting process for offshore wind farms. Secondly, it is hoped that this software tool will help to streamline the micro-siting process. By combining an optimization algorithm with energy and cost models for the major components of an offshore wind farm, the cost of energy (COE) can be minimized while accounting for real-world constraints imposed by the specific site.

The OWFLO tool is being designed to perform two functions: layout analysis and layout optimization. A simple, proof-of-concept analysis routine has recently been developed. The software combines individual cost and energy models (shown later in Figure 3) to estimate the investment costs and energy production of an offshore wind farm as specified by the user. The

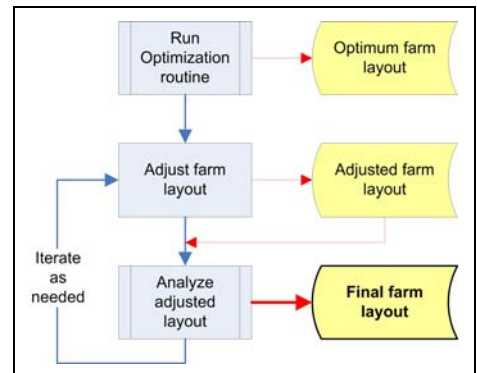


Figure 2. The optimization and analysis routines can be used together to refine a wind farm layout

optimization routine will be developed next and will allow the software to search for the layout configuration with the lowest COE and/or the greatest energy production, again based on the results of the models. 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.

B. Background

Determining the optimum layout for an offshore wind farm involves many tradeoffs. For example, 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. Several other such tradeoffs exist. Most commercial wind farm layout software uses only the energy production to evaluate a layout, and thus they can not be used to address these cost and energy tradeoffs. This project, therefore, includes the development of a simple software tool which can be used to study both the costs and energy production involved in offshore wind farm micrositing.

The offshore wind farm literature provides several examples of previous studies which discuss topics related to the various costs and energy models needed for the OWFLO project. These studies encompass scaling relations for various turbine components to non-wind-related studies in placement optimization. A brief summary of this literature follows.

1. Wind farm costs

Several major European projects have looked at the scaling of wind farm components. One was the Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS) study². 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 Opti-OWECS and OWECOP (Offshore Wind Energy – Cost and Potential)³ projects identified the most important cost components for offshore wind farms (Table 1). This list of components served as a starting place for the list of component models developed during the first phase of the OWFLO project. The OWECOP project is currently underway at the Energy research Centre of the Netherlands (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 with a Geographic Information System (GIS). It is similar in concept to the OWFLO project, but the OWECOP project is focused on the overall siting of the wind farm itself, whereas the OWFLO project considers micrositing within the farm.

The Dutch Offshore Wind Energy Converter (DOWEC) project⁴ looked at ways of improving offshore wind turbine design and increasing their cost-effectiveness. The project identified ways to design and build better, more reliable large turbines (5-6 MW) for large (100s of MW) farms in the near-future. The DOWEC study, conducted from 1997 - 2003, examined electrical, O&M, support structure, and rotor-nacelle assembly

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 |

Some of the cost relationships given in the reports have been adapted for use in the OWFLO project.

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 report⁵. Their latest report gave several relations for wind farm costs, but stated that further work on the optimization and layout capabilities was required. Of these, only WindFarm has the capability to optimize layouts by minimizing the COE.

2. Turbine wakes

Considerable effort has gone into understanding turbine wakes in offshore environments. A good example of this effort is the Efficient Development of Offshore Windfarms (ENDOW) project⁶, which sought 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 Risø National Laboratory in Denmark and included models from ten organizations in Europe. During the project, improvements to each of the wake models were identified and implemented. The models compared in the ENDOW project varied in complexity, from processor-intensive CFD models, to more simple analytical models like the PARK model given in Equation (3) below. The overall result of the comparison was that no one model or type of model was able to predict single or multiple wakes better than the others.

3. Placement optimization

The next task in the OWFLO project is the development of the optimization routine. Typically, gradient (“hill-climbing”) optimization methods are able to find local minima (e.g. minimum COE), but not necessarily the overall minimum. On the other hand, analyzing each possibility to find the overall minimum becomes computationally intensive. None of the wind farm optimization papers reviewed used gradient methods. Instead, the preferred methods involved a small element of randomness to dislodge the solution from the local minima. From the literature, two such approaches were suggested: heuristic and genetic optimization algorithms. Heuristic optimization involves random addition, subtraction, and/or change of position of turbines, whereas genetic optimization subjects the turbine locations to the process of genetic mutation. The applicability to wind energy of each of these methods has been investigated and is available in the literature. For example, see the study from Hawaii Pacific University and the University of Pittsburgh⁷ for information of a heuristic algorithm. Additional information on the use of genetic algorithms can be found in several studies⁸⁻¹⁰.

III. Project description and methodology

A. Project schedule

The analysis routine and simple component models were the foci of the first phase of the project, which has now been completed. Where models were not been found during the literature search, simple models were developed. A graphic user interface was also created to allow for easy interaction with the models. The results from these simple models are now able to be compared to data from existing wind farms. One such comparison with the Middelgrunden offshore wind farm is discussed in Section IV below.

In the second phase of the project, the optimization routine is being developed and the component models are being improved. The third and final phase of the project will use the optimization and analysis routines to perform an in-depth analysis of the cost and energy trade-offs involved in offshore wind farm micro-siting. This project has a target completion date of December 2006.

B. Software tool

The structure of the OWFLO software tool is modular (see Figure 3) which provides a great deal of flexibility: as improvements are made to the component models, they can be implemented without requiring major revision of the code. For example, if alternate wake models are added, the modular structure will allow the user to select the wake model they wish to use.

One of the objectives of the optimization is the minimization of the COE. The measure of the COE used in this project is the levelized production cost (LPC), which represents the cost per kWh of the wind farm to its owner. In the standard formulation of the LPC, given in Equation (1), the cost and energy production functions (in the numerator and denominator, respectively) are independent. Furthermore, the cost function is made up of several component costs which are also independent. Equations (1) and (2) show how the component models

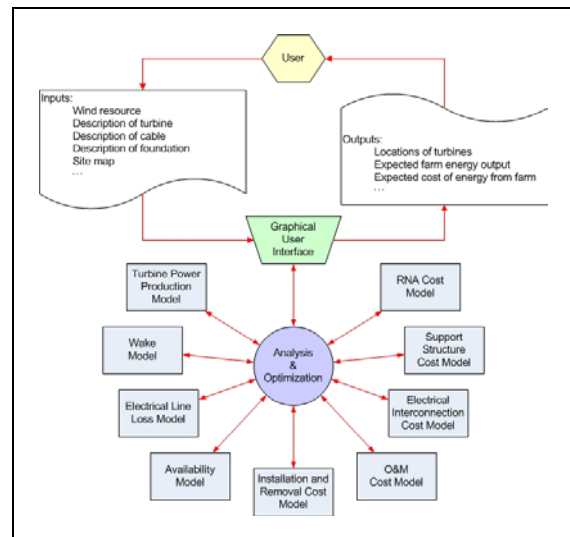


Figure 3. Modular structure of OWFLO software

are used in the estimation of the LPC. C_c is the capital cost of the farm, C_y is the annual cost, a is the annuity factor, and E_y is the annual energy production.

$$LPC = \frac{C_c}{a \cdot E_y} + \frac{C_y}{E_y} \quad (1)$$

$$= \left[\frac{C_{RNA} + C_{support\ structure} + C_{electrical} + C_{install-remove}}{a \cdot E_y} \right] + \left[\frac{C_{O\&M}}{E_y} \right]$$

$$E_y = \sum_{N_i} [(E_i - (wake)_i - (collection)_i) \cdot (avail)_i] - (transmission) \quad (2)$$

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 cost and energy functions separate, this phenomenon is treated using two models: the electrical interconnection cost model and the electrical line loss model. Other linked phenomena such as O&M and availability are separated in a similar manner.

C. Component models

Initial component models, which are simple but give reasonably realistic results, have either been chosen or developed. These component models are shown in Figure 3 and are also listed with their input parameters in Table 2. During the second phase of the project, these models are being refined.

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 references¹¹⁻¹⁴. These algorithms use characteristics of the RNA (e.g. mass, hub height, and rotor diameter) and soil properties as inputs and return component masses, costs, and dimensions. It should be noted that 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. Availability, installation cost, and O&M cost

No complete mathematical models for offshore wind farm availability, installation cost, or O&M cost were found in the literature. Many studies have investigated availability, component failure, and maintenance strategies^{15,16}, but estimating these complex quantities remains a complicated process. Until mathematical models capable of dealing with this complexity have been developed, very simplified models will be used instead. For example, a simple 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 report¹⁷, an annual O&M cost equal to 2% of the capital cost was chosen.

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 PARK wake model described by Katic et al.¹⁸, Jensen¹⁹, and Sanderhoff²⁰, which has been cited in many simple turbine wake studies, is used:

$$Deficit = \left(1 - \frac{U}{U_0} \right) = \frac{2b}{\left(1 + k \frac{x}{R} \right)^2} \quad (3)$$

Here, k is the wake spreading constant proposed by Frandsen²¹:

$$k = \frac{0.5}{\ln\left(\frac{z_H}{z_0}\right)} \quad (4)$$

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. It should also 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. Wake deficits from multiple turbines are combined by summing the squares of the interacting deficits, as suggested in Katic et al.,¹⁸ among others:

$$\left(1 - \frac{U}{U_0}\right)^2 = \sum_i \left[\left(1 - \frac{U_i}{U_0}\right)^2 \right] \quad (5)$$

Table 2. Component models and their input parameters

| Modeled quantity | Input parameters |
|---------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Rotor-nacelle assembly (RNA) cost | turbine rated power |
| RNA mass | rotor diameter |
| Support structure mass | |
| Tower | turbine rated power, rotor diameter, turbine hub height |
| Monopile | tower base diameter, turbine hub height, water depth, rotor thrust, allowable soil pressures |
| Gravity base | tower mass, RNA mass, rotor thrust, turbine hub height, allowable bearing capacity of soils |
| Support structure cost | |
| Tower | tower mass, cost coefficient |
| Monopile | mass of monopile, cost of steel |
| Gravity base | mass of gravity base, cost of concrete |
| Electrical interconnection cost | cable voltage rating, maximum farm power, cable length |
| O&M cost | wind conditions, probability of various types of failures, off-site time needed for each type of failure, on-site time needed for each type of failure, distance to shore for each turbine, transportation requirements (e.g. vessel type) ^a |
| Installation and decommissioning cost | wind conditions, water depth, soil conditions, probability of various types of failures, off-site time needed for each type of failure, on-site time needed for each type of failure, distance to shore for each turbine, transportation requirements (e.g. vessel type) ^a |
| Single turbine power production | turbine power curve, wind speed |
| Multiple turbine wake losses | placement of turbines in farm, wind direction, rotor diameter, turbine hub height, rotor thrust coefficient, surface roughness length |
| Electrical cable losses | cable voltage rating, maximum farm power, cable length |
| Turbine Availability | wind conditions, probability of various types of failures, off-site time needed for each type of failure, on-site time needed for each type of failure, distance to shore for each turbine, transportation requirements (e.g. vessel type) ^a |

^a The parameters listed for these three models will be implemented in the next revision of these models. The current models use various percentages.

IV. Initial results

In order to investigate the accuracy of the component models, cost and energy data from the Middelgrunden offshore wind farm were compared with modeled results. The Middelgrunden farm is located about 3 km outside Copenhagen harbor in Denmark. It consists of 20 Siemens (formerly Bonus) 2 MW turbines which are installed on gravity base foundations in 3-6 m water. Wind and power data were obtained from the Middelgrunden Wind Energy Cooperative (MWEC) which owns the southern 10 turbines. Economic data for the MWEC turbines are also available from the project website²². The availability of these economic and production data makes Middelgrunden an ideal farm with which to compare the OWFLO models.

Data for the 10 MWEC turbines from October 16, 2001 to October 16, 2002 were used in this comparison. During this period, the MWEC turbines produced 50.9 GWh and the OWFLO models estimated 51.8 GWh.

The budgeted LPC was approximately 4.6 ¢/kWh, based on the assumed production guaranteed by the manufacturer of 44 GWh. The combination of the estimated energy production and the actual capital and O&M costs gave an estimated LPC of 3.7 ¢/kWh. When the component cost models were used instead, the estimated LPC was 5.5 ¢/kWh. This increase is due primarily to the difference in actual and estimated RNA costs. A break-down of the estimated and actual costs is given in Table 3. These costs have been converted from Danish Krone (DKK) to US dollars using an average rate of 8 DKK/\$ for the year 2000. It is clear that the RNA cost model over predicted the costs for these turbines. Otherwise, however, the modeled results are encouraging. As the OWFLO project moves forward, the discrepancies should be reduced.

The Middelgrunden analysis was also used as the basis for a sensitivity analysis of the impact of the component models on the LPC. For the most realistic comparison, the actual costs were used in the analysis. These costs and the results from the individual energy component models were varied by $\pm 5\%$. The resulting LPC values are shown in Figure 4. Overall, individual energy models have more of an impact on the LPC than individual cost models, with the turbine wake model having the most impact. The other three energy models have the same impact because each simply multiplies the energy production by $\pm 5\%$.

Table 3. Comparison of modeled and actual cost break-down for the Middelgrunden offshore wind farm

| Wind farm component | Actual cost (\$ million) | Estimated cost (\$ million) |
|-----------------------------------------|--------------------------|-----------------------------|
| Rotor-Nacelle Assemblies | 12.4 | 20 |
| Towers ^a | included in above | included in below |
| Sub-structures ^a | 6.0 | 6.0 |
| Electrical interconnection ^b | 2.1 | 1.9 |
| Other (e.g. installation) | 2.1 | 3.1 |
| Total capital cost | 22.6 | 31 |
| Annual operation and maintenance | 0.33 (budgeted) | 0.62 |

^a The RNA model under-predicted the mass of the RNA (103 tonnes). In order to more accurately estimate the tower and sub-structure costs, the actual RNA mass (125 tonnes) was used in these two cases.

^b The MWEC did not pay for the transmission cable. This cable was purchased and installed by Copenhagen Energy, the owner of the northern half of the wind farm.

V. Conclusions and future work

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 a measure of the COE, such as the LPC. This type of software will be particularly useful as developers look at sites farther from shore and in deeper waters.

A simple software tool has been created to estimate the costs, energy production, and the LPC for offshore wind farms.

Cost models exist in the literature for some of the most expensive components of an offshore wind farm. When relevant models were not found, simple models were developed.

Energy production, project cost, and LPC values have been estimated and compared with the actual or budgeted values from the Middelgrunden offshore wind farm. These comparisons show that the estimated energy production is quite close to the actual production. The estimated electrical collection and gravity support structure costs are also close to the actual values. The RNA cost model overestimated the RNA cost by 65%.

A sensitivity analysis was performed to determine the impact of changes to the various component models on the LPC. The turbine wake model was found to have greatest impact: a 5% increase in the wind speed deficit resulted in almost a 12% increase in the LPC. The other energy component models were shown to have a greater impact on the LPC than the individual cost component models.

The component models are currently being improved. The next task is the development and implementation of the optimization routine.

Finally, using the optimization and analysis routines, an investigation of the cost and energy trade-offs inherent to offshore wind farm micro-siting will be performed. By understanding these trade-offs, methods by which to further reduce the cost of offshore wind energy may be identified.

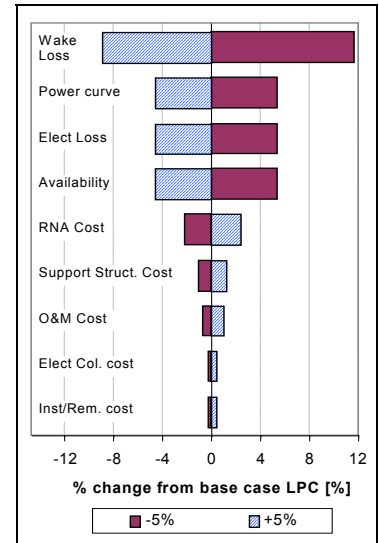


Figure 4. Sensitivity of LPC to component models

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