

Application of an offshore wind farm layout optimization methodology at Middelgrunden wind farm

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ABSTRACT

This article explores the application of a wind farm layout evaluation function and layout optimization framework to Middelgrunden wind farm in Denmark. This framework has been built considering the interests of wind farm developers in order to aid in the planning of future offshore wind farms using the UK Round 3 wind farms as a point of reference to calibrate the model. The present work applies the developed evaluation tool to estimate the cost, energy production, and the levelized cost of energy for the existing as-built layout at Middelgrunden wind farm; comparing these against the cost and energy production reported by the wind farm operator. From here, new layouts have then been designed using either a genetic algorithm or a particle swarm optimizer. This study has found that both optimization algorithms are capable of identifying layouts with reduced levelized cost of energy compared to the existing layout while still considering the specific conditions and constraints at this site and those typical of future projects. Reductions in levelized cost of energy such as this can result in significant savings over the lifetime of the project thereby highlighting the need for including new advanced methods to wind farm layout design.

1. Introduction

As offshore wind farms continue to grow it has become increasingly important to ensure that these projects are managed as efficiently as possible. With this in mind, the field of offshore wind farm layout optimization has grown to include sophisticated methodologies for the evaluation of the levelized cost of energy (LCOE) of offshore wind farms which includes both the lifetime energy production and lifetime costs of the wind farm. The LCOE, is frequently used by project developers to evaluate the impact a change in design might have on a project. This metric is also preferred as it is technology agnostic and therefore gives a basis by which projects of different technology types can easily be compared against one another.

The present work expands on the standard paradigm for the optimization of offshore wind farm layouts in which wake and cost models are integrated as the evaluation function for an optimization algorithm. This work shows that a sophisticated and detailed LCOE evaluation tool can successfully be included in the optimization process accounting for realistic constraints faced by a wind farm developer. Taking the UK Round 3 wind farms as a point of reference, the present

tool built in partnership with wind farm developers, has been developed to aid in the planning of these wind farms allowing the developer to explore wind farm layout alternatives. Given the future application to UK Round 3 sites, much of the tool has been calibrated to these sites and sites of similar site characteristics. Extending the previous work of the authors (Pillai et al., 2016), the present work allows the wind farm to be designed considering different degrees of layout restriction which may potentially be imposed by regulatory bodies.

This article explores Middelgrunden wind farm, a wind farm off the Danish coast, as a test case to both verify the full LCOE evaluation function and highlight potential improvements that could have been achieved through more optimal turbine placement using either a genetic algorithm (GA) or a particle swarm optimizer (PSO). By applying the layout optimization framework to a real wind farm site rather than to fictional cases the capabilities and applicability of the present wind farm layout optimization tool are demonstrated.

The field of wind farm layout optimization was initially explored in the seminal work by Mosetti et al. (1994) in which three fictional wind farm sites were defined and wind farms optimized using a genetic algorithm. Following the inception of the field of optimization of wind

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farm layouts, the cases defined by Mosetti et al. (1994) have been revisited and used as a benchmark. The field has explored a number of different optimization algorithms to this problem including genetic algorithms (Grady et al., 2005; Elkinton, 2007; Elkinton et al., 2008; Mittal, 2010; Huang, 2009; Couto et al., 2013; Geem and Hong, 2013; Chen et al., 2013; Zhang et al., 2014; Shakoor et al., 2016), particle swarm optimizer (Chowdhury et al., 2013), viral based optimization (Ituarte-Villarreal and Espiritu, 2011), pattern search (DuPont and Cagan, 2012), mixed-integer linear programming (Fagerfjäll, 2010), and Monte Carlo simulation (Marmidis et al., 2008). The most frequently deployed optimization approach has been the genetic algorithm and though much work has focused on the development and evolution of the optimization algorithm, little of the existing literature has explored the evolution of the evaluation function beyond testing alternate wake models. Detailed reviews in the field of wind farm layout optimization have been compiled by Tesauro et al. (2012) and Herbert-Acero et al. (2014).

As the original work by Mosetti et al. (1994) explored the applicability of the genetic algorithm to this problem, it ignored the layout dependent costs. Many of the developed tools following this have also focused on the applicability and development of the optimization and have therefore opted to use cost functions that either omit important layout dependent factors or which ignore the layout all together thereby only considering the impact the layout has on the energy produced. The work by Elkinton (2007) represents an exception in which a detailed cost model was built and verified. This, however, was developed based on published data at the time and has limited applicability to new projects. As the aim of the existing tools has been to further develop the optimizers rather than industrial applications of the methods, it remains challenging for the developed wind farm layout optimization tools and methodologies to be deployed in the design of real offshore wind farms. Focusing more on the potential industrial applications, the present work therefore both represents a more detailed evaluation function over previous work and also applies the full methodology to a more complex wind farm site with realistic constraints faced by developers. Furthermore, the development of the present framework has allowed two of the leading metaheuristic optimization algorithms applied to offshore wind farms to be deployed on the same framework allowing a direct comparison.

Through the deployment of this tool for an existing wind farm it is possible to gauge the tool's suitability to future wind farms and identify areas in which the tool will need to be further developed in order for the results to be of use to a site developer.

2. Methodology

The developed approach makes use of a modular framework for the assessment of offshore wind farm layouts. As is shown in Fig. 1, the evaluation of a layout is divided into three separate steps. The LCOE by definition requires the computation of the AEP and the lifetime costs as shown in Eq. (1), however, a wind farm's electrical infrastructure (substation position, intray-array cable paths, and intra-array cable

specifications) impacts both of these terms; changes in the electrical infrastructure affect the energy losses and therefore the AEP while at the same time changes in the electrical cabling and substation position can directly affect the costs. The first step in the evaluation of the LCOE is therefore for the necessary electrical infrastructure to be determined for a given turbine layout. Following this, the annual energy production (AEP) for the wind farm is computed considering not only the wake losses, but also the losses due to the electrical infrastructure; and finally, the relative costs of the project over its lifetime are estimated. From these three components, the LCOE of the layout is computed and as a result, the optimizers can use this information to make informed decisions on how the solutions should evolve between generations.

The LCOE is defined to be a function of both the total energy generated and the costs over the lifetime of the wind farm:

$$LCOE = \frac{\sum_{t=1}^n \frac{C_t}{(1+r)^t}}{\sum_{t=1}^n \frac{AEP_t}{(1+r)^t}} \quad (1)$$

where C_t is the total costs incurred in year t , n is the project lifetime, AEP_t is the annual energy production in year t , and r is the discount rate of the project.

As European regulators are currently in discussions with wind farm developers to develop guidance on how layouts are to be designed in the future, there are different levels of constraint which are of interest to developers depending on the final decisions made by the regulators and licensing bodies (NOREL Group, 2014). In order to accommodate these different levels of constraint, the present framework has three separate modes of operation which address these different constraints:

- 1. Array mode** - The decision variables define the spacing and orientation of a regular grid of turbine positions with constant downwind and crosswind spacing throughout the site. This produces layouts with clearly defined navigational channels and is preferred by some regulators due to stakeholders concerns such as those raised by the Maritime Coastguard Agency in the UK (NOREL Group, 2014).
- 2. Binary mode** - The wind farm area is discretized into allowable turbine positions and the decision variables are therefore binary variables representing the presence of a turbine in a particular cell. Wind farm developers are interested in this approach as it allows them to have much of the regularity that regulators seek with the array mode, but could allow for more innovative layouts that better use the site in question. In this scenario, the discretized allowable turbine positions could be imposed directly with the regulator or be developed through discussions between the wind farm developer, regulator, and other stakeholders.
- 3. Continuous mode** - The decision variables directly define the turbine coordinates and may therefore occupy any value within the wind farm area. Using these constraints, there are no externally regulator/stakeholder imposed constraints on the positions of the turbines and this therefore represents the case in which the wind farm developer is free to develop the site as they see best.

2.1. Electrical infrastructure optimization

As part of the development of this layout optimization framework, a sub-tool has been developed to address the optimization of an offshore wind farm's electrical infrastructure. This is fully presented by in Pillai et al. (2015a). This sub-tool implements a heuristic approach and is therefore not guaranteed to find the proven optimal solution, however, it takes a pragmatic approach, identifying good feasible solutions in an acceptable run time. As part of this sub-tool, given the turbine positions, number of offshore substations, voltage level of the connection network, and the cable parameters, the offshore substation positions are determined as well as all intra-array cable paths, and

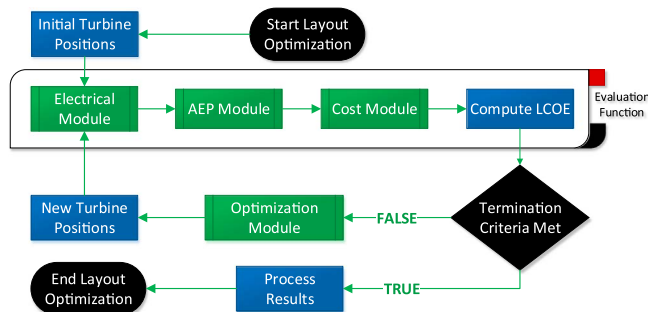


Fig. 1. Modular approach to wind farm layout optimization.

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