

Investigation of offshore wind farm layouts regarding wake effects and cable topology

Bryce Wade

Bryce.wade@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract— Offshore wind energy is emerging as a large contributor to installed renewable energy capacity. In order to continue the momentum of its development, the offshore wind industry is looking to continually lower the levelized cost of electricity (LCOE). One area being explored in an effort to lower the LCOE of offshore wind generation is the optimization of the wind farm layout. Many of the offshore wind farm layout designs that exist today are structured in a rectilinear form where turbines are spaced evenly along columns and rows. This thesis explores the economic advantages of removing rectilinear constraints and optimizing the positions of the individual turbines within an offshore wind farm.

At the core of achieving the thesis objective was the development of a model that is capable of simulating an existing offshore wind farm by converting representative wind farm data into an LCOE. The positions of the turbines within the wind farm can be modified using an optimization framework with the intent to minimize the LCOE. The model comprised of the Jensen Wake Model, a hybrid cable layout heuristic and an NREL cost scaling model. The wind farm layout was optimized using a genetic algorithm.

The cost estimation model and optimization framework were applied into two case studies to analyze the results of the wind farm layout optimization of two wind farms, Horns Rev and Borssele. In both case studies the optimized layouts provided higher AEP, shorter intra-array collection cable lengths and ultimately a lower LCOE than the baseline rectilinear layouts.

Keywords- Offshore Wind Energy, Wind Farm Layout Optimization Problem, Wake Effects, Cable Topology, Genetic Algorithm

I. INTRODUCTION

A. Background

Developing carbon free sources of electricity has become a global focus in recent decades. As the understanding of the importance of this shift within the energy sector spreads, increased interest and investment have been directed towards renewable energy sources in an effort to expedite the transition. Wind energy is a leading technology in the development of large-scale renewable energy generation and is a significant percentage of the electricity generation of many nations. [1] [2]

Offshore wind energy in particular is an emerging technology that is becoming increasingly viable as improvements in technology are driving down the levelized cost of electricity (LCOE) making it more competitive with onshore wind technology and other forms of electricity generation.

One particular area being explored in an effort to lower the LCOE of offshore wind generation is the optimization of the wind farm layout. There are multiple parameters that are considered when designing a wind farm array including but not limited to: wake effects, wind profile, bathymetry, soil types, cable installation costs, transmission losses, environmental concerns, permitting restrictions and aesthetics. While acknowledging these parameters, many of the resulting wind farm layout designs that exist today are structured in a

rectilinear form where turbines are spaced evenly along columns and rows. This is the case for many notable large projects such as Horns Rev, London Array, Gemini Wind Farm and Dudgeon.

Wind farm designers have considered the value of minimizing wake effects, as the rows and columns of wind farms are often oriented into an optimal direction based on the local wind climate. However, the inconsistent nature of environmental factors such as the local wind climate, bathymetry, and soil types would conclude that these are not driving factors in the structured layouts.

It has been hypothesized through many academic research efforts that keeping rectilinear formats may cost a great deal when measuring the annual energy production over the lifetime of the windfarm [3].

When determining the spacing between turbines in an offshore windfarm layout, there are two key parameters that oppose with regards to profitability; wake effects and the collection cable length. As the turbine spacing increases, the wake effects decrease which results in an increase in the annual energy production. Though increased space between turbines results in longer collection cables and in turn, higher transmission losses and increased cable costs. The opposing nature of these design variables result in some layouts being more profitable than others.

Abandoning the rectilinear constraints described above and understanding how the wake effect and cable cost variables are related can be utilized in the wind farm design process to improve the economic viability of offshore wind development.

B. Project Objective

This work explores the advantages of optimizing the positions of the individual turbines within an offshore wind farm. The optimization seeks to minimize the objective function which is LCOE of an offshore wind farm. At the core of this work was the development of a model that is capable of the following:

- Simulating an existing offshore wind farm by converting necessary input data into a representative LCOE.
- Providing the ability to optimize the positions of the individual turbines within the wind farm in order to lower the LCOE.
- Providing the ability to perform sensitivity analysis for different input parameters for the offshore wind farm that can provide insight to the importance of the different design variables.

The model was validated using measured data from an existing wind farm. Upon validation, the model was used to estimate the difference in LCOE's for different wind farms with the existing and optimized wind farm layouts and conclusions were drawn from the results.

II. STATE OF THE ART

A wind farm consists of an array of wind turbines that convert the kinetic energy from the wind to electricity. Wind turbines can be arranged within a wind farm in a certain orientation in order to increase the energy the wind farm yields. Traditional layouts are typically in a rectilinear format, identifiable by the turbine's arrangement in equally spaced rows and columns. The majority of the largest wind farms in operation today are in a grid format, rotated in an orientation with respect to the wind direction to maximize energy yield (for the set formation). However there has been a growing field of research into truly maximizing the energy yield for a given wind farm site by abandoning the rectilinear constraints. The area of this research has been termed the Wind Farm Layout Optimization Problem (WFLOP) where interested parties are creating models and using optimization algorithms to better understand how different wind farm orientations can provide higher energy yields under different environmental and physical circumstances. [3]

A. Wind Farm Layout Optimization Problem

The WFLOP requires a defined objective function and an optimization strategy. The objective function is calculated based on the design parameters, and is minimized through optimization of the wind farm design.

The optimization strategies use algorithms that iterate through various scenarios in search of satisfying constraints and minimizing the objective function. The optimization algorithms can be categorized into gradient methods [4], genetic algorithms [5] [6], viral algorithms [7], particle swarm algorithms [8] and greedy heuristic algorithms [9]. [10]

The WFLOP was first explored by Mosetti et al. [5] in 1994 by considering a wind farm that did not have a defined desired power output, but a fixed number of potential turbine positions. The wind farm consisted of a 10x10 grid where the wind turbine could be placed in the center of each quadrant or not, in search of the most profitable design based on the objective function. Since the work of Mosetti et al. there have been numerous attempts to determine the best methods for designing a wind farm layout. The research that followed Mosetti et al. can largely be categorized into two paths: (1) a track focused on the development and testing of different optimization strategies i.e. optimization algorithms, [6] [8] [9] and (2) a track focused on improving the wind farm model accuracy [11] [12]. [3] The second path concentrates on the inclusion of more comprehensive sub-models that consist of an increasing number of parameters in an effort to make the simulations more representative and applicable.

Hebert et al. [3] provided a comprehensive review of the state of the art of wind farm design and optimization. Hebert et al. reviewed over 150 works and found that the most common objective functions being used were the maximum AEP and minimum COE. The most common wake model used within WFLOP research to date is the Katic-Jensen model. This is in large part due to its modelling simplicity which lessens the computational demand and decreases the simulation time. Hebert et al. concluded that computational technologies are typically the limiting factor for the treatment of the WFLOP problem. Beyond improvement of computational restraints, Hebert et al. concluded that the most important research trends

in WFLOP are focused on improving the formulations describing the expected energy conversion of the wind farm, the wind turbine wakes and turbulence impacts, the wind turbine structural fatigue and degradation, the various types of environmental impacts, the overall electrical system losses and reliability and the uncertainty and risk management.

III. MODEL DEVELOPMENT

The objective of the model optimization, as previously stated, is to optimize the positions of the turbines within a wind farm in an effort to minimize the LCOE. There are two variables within Equation 1 that are dependent on the positions of the turbines (all else were considered independent within this work); Initial Capital Costs (ICC) and the annual energy production (AEP). More specifically within the ICC, it is the intra-array cable costs that are dependent on the wind turbine positions.

$$LCOE = \frac{ICC * FCR}{AEP} + AOE \quad (1)$$

The modelling framework developed in this work is explained easiest by breaking down the three core components. The physical component included sub-models that provided collection cable lengths and annual energy production for a given wind farm based on its layout. The economic component utilized the cable length and AEP to generate an LCOE. The optimization component used the LCOE as its objective function and modified the turbine positions in search of an optimal layout.

A. Physical Component

The physical component accounts for the environmental and physical characteristics of the wind farm and provides the annual energy production and collection cable layout. The two core sub-models within the physical component pertain to the wake effects and the cable topology.

1) Wake Effects

As a turbine extracts energy from the wind and converts it to electrical energy, it leaves a wake behind which is characterized by reduced wind speeds and increased turbulence in the flow [13]. The wake from a turbine expands and gradually returns to the free stream condition as it continues downstream. If the wake of a turbine intersects with the swept area of another turbine downstream prior to reaching the free stream condition, the downwind turbine is considered to be shadowed by the upstream turbine [14]. If a turbine is shadowed, it experiences a lower wind velocity than the free stream, which can result in less energy conversion than if the turbine was not shadowed.

2) Jensen Model

The Jensen Model is one of the oldest and most widely used wake prediction models. A benefit to the use of the Jensen model is that it is a relatively simple model that is less computationally demanding than others and has still been proven to provide comparably accurate results [15] [16] [17].

A key assumption to the Jensen single wake model is that mass¹ is conserved in the direction of the turbine axis [18]. The total velocity deficit of the wind velocity at position x due to the wake effects from an upstream turbine can be given by Equation 2 [18].

$$1 - \frac{v_1}{v_0} = \frac{1 - \sqrt{1 - C_t}}{\left(1 + \frac{2 \alpha x}{D_0}\right)^2} \quad (2)$$

Equation 2 assumes the complete downstream turbine is within the wake. To account for when a turbine experiences only a portion of the linearly defined wake, a simplification was implemented using a binary partial wake model. When the rotor area is partially in the wake of another turbine, it was assumed that if half or more of the turbine's swept area was affected by the wake, then the full wake would be considered. If less than half of the turbine's swept area was affected by the wake, the wake would not be considered.

When having multiple wakes interacting with one another, it is assumed that the kinetic energy deficit of a mixed wake is equal to the sum of the energy deficits for each wake acting on a given position. This can be expressed by Equation 3 for a turbine in the wake of two others [18].

$$v_i = v_o \left[1 - \sqrt{\sum_{i=1}^{N_t} \left(1 - \frac{v_i}{v_o}\right)^2} \right] \quad (3)$$

3) Intra-array Collection Cable

The intra-array collection cable system gathers the electricity from each individual turbine and connects it to a substation. The subsea cables drop from the individual turbines to the sea bed and are typically buried 1 to 2 meters in the seabed. Current collection systems are medium voltage, and depending on the project can range from 10 to 35 kV [19]. There are a number of design strategies for the layout of collection cables, each with their own strengths and drawbacks. The two selected within this work are discussed briefly below.

The simplest design strategy for a collection system is the radial design which connects a series of turbines on a single cable. The number of turbines per cable is determined by the maximum power output from each turbine and the maximum rated capacity of the cable. The radial design is considered to be advantageous because it uses minimal cable, but its drawback is that it does not account for any redundancy [20].

The branch design is less common for offshore wind farm designs, but is frequently used in communication networks and has desirable features for use in collection cable design. The branch design, provides opportunity for lower cost and higher reliability than the currently most common approach, the radial design. [19]

In order to adequately compare wind farm layouts, the model required a cable layout method that provided consistent radial/branched results between rectilinear layouts and irregular layouts.

4) Cable Layout Heuristic

A hybrid cable layout heuristic developed by Katsouris [19] that combined the planar open savings (POS) heuristic and the

Esau-Williams heuristic was implemented. The heuristic acted as a nested optimization within the physical model that efficiently designed a near optimal cable layout using the strengths of the POS heuristic and the EW heuristic.

The POS heuristic was developed by Bauer and Lysgaard [21] and is one of the most efficient heuristic algorithms for the radial internal connection of offshore wind farms [19]. The POS heuristic begins with an initial solution of every wind turbine being connected directly to the substation. In every step the savings heuristic considers merging two routes (cables) into one cable. The savings associated with this merge are logged, and in every step the heuristic greedily chooses the merge with the highest savings resulting in a route not exceeding capacity [21]. The heuristic continues until all savings are achieved under the given constraints and capacities and a near optimal solution is reached.

The EW heuristic is a saving procedure which, similar to that of the POS heuristic, starts from a star tree formation of the turbines and substation connections. In each iteration, the merging of two routes is determined by the option that provides the largest savings [22]. Relative to the POS heuristic, the EW provides more freedom and possibilities for merging routes since there is no limitation on the position of the turbines in their corresponding routes. The main characteristic of the EW heuristic is that it attempts to connect the turbines further from the substation into clusters first, and then upon a cable reaching its full capacity, the algorithm continues with creating a new cluster closer to the substation [19].

B. Economic Component

The economic component's function is to use the AEP and cable layout obtained from the physical component and to assign values to the outstanding variables required to provide the LCOE for the wind farm (See Equation 1). These outstanding variables include the annual operating expenses (AOE), bottom lease cost (BLC), operations and maintenance (O&M), levelized replacement cost (LRC), fixed charge rate (FCR) and most significantly the remaining parameters within the ICC. The ICC is the sum of the turbine system costs and the balance of station costs.

$$AOE = BLC + \frac{O\&M + LRC}{AEP} \quad (3)$$

The Wind Turbine Design Cost and Scaling Model developed by Fingersh et al. [23] was selected to be the basis of the economic model for all of the fixed costs because of the simplicity of the parameters required. The model is intended to provide reliable cost projections for wind generated electricity based on different turbine and wind farm sizes. This was an important characteristic for implementation into a model that intends to be used for a variety of wind farm and wind turbine sizes. It is understood that at the time of publishing the Fingersh et al. model, the components directly related to offshore technology were in their infancy and the forecasts are considered extremely rough. The cost estimates are projected based on only the turbine power rating, rotor diameter, hub height, as well as a few inflation and cost of material variables,

¹ Katic et al. [8] incorrectly state "momentum is conserved".

all of which remain unchanged throughout the optimization process.

Modifications were required for the electrical cost estimates within the ICC for the cost scaling model developed by Fingersh et al. The collection cable costs within the model were dependent on the rated power of the turbine, and not the cable topology which was a core feature of the model being developed. Therefore, appropriate modifications were made by using components of an additional NREL model developed by Green et al. [24] focused primarily on electrical collection and transmission systems for offshore wind power.

The LCOE results from the economic component are estimated values with the purpose of being used for comparison between wind farm layouts with the same economic parameters. Assumptions and limitations, as well as explanations for the derivations of the empirical cost scaling models can be found at [23] [24].

C. Optimization Component

A genetic algorithm was selected for the optimization of the wind farm layout primarily based on the research into other WFLOP. Genetic algorithms are probabilistic search algorithms which are designed to mimic the logic of natural selection. Genetic algorithms work by generating populations of individuals (wind farm layouts) that consist of a set number of variables (x and y coordinates for each turbine). The objective function for each individual (LCOE of each windfarm layout) is calculated for the entire population. The population is evaluated based on the desired stopping criteria for the optimization and if the criteria is met the optimization process is complete. If the stopping criteria is not met, the population goes through a genetic manipulation process where the elite individuals (wind farm layouts with lower LCOE) are passed on to the following population and other individuals are selected to become parents in the following generation. Once the parent individuals have been selected, a crossover operation is used to combine the traits of the parent individuals. The final step in the genetic manipulation process is the mutation phase in which there are random alterations made to the population. These random alterations are important for incorporating new information into the population that increase the likelihood of testing more of the result surface [25]. The children individuals that were created from the parent individuals are then evaluated against the optimization stopping criteria to determine whether or not another genetic manipulation process is required. There are different parameters and strategies that can be implemented for each stage of the genetic manipulation which is described further by Pohlheim [26].

External constraints were applied to the genetic algorithm that sectioned the wind farm into tiles where only one turbine could be micro-sited within each tile as seen in Figure III-1. The wind turbine could be placed anywhere within each tile so long as it also satisfied the additional Jensen model constraint which ensures no turbines were closer than 3 diameters to one another. This feature provided some structure to the wind farm which may be desirable for designers, but more importantly it limited the function result surface which reduced the computational demand of the optimization process.

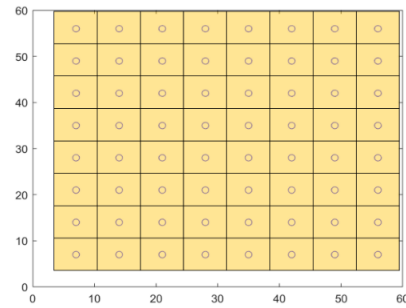


Figure III-1: Wind Farm Layout Optimization Constraint

IV. MODEL VALIDATION

Validation was carried out once the model was completed and model behaviour within the design space was analyzed. The wake model validation compares results from the present model with measured data from an existing wind farm.

Horns Rev wind farm (seen in Figure IV-1) was used for model validation due to the amount of publicly available information [27] [28] [29]. The information necessary for validation is the physical and environmental characteristics of the wind farm (turbine power and thrust curves, wind rose and Weibull distribution parameters, etc) as well as the measured annual energy production of the wind farm. Additionally, measured power data for individual machines is required to validate the wake model specifically by analyzing the wind velocity deficits at particular turbines in different locations within the wind farm.

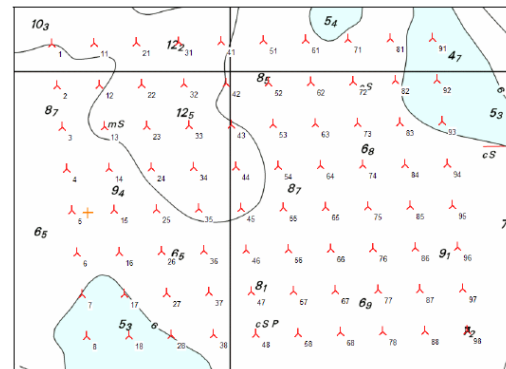


Figure IV-1: Horns Rev wind farm layout

A. Wind Velocity Deficit Validation

The wind velocity deficit can be defined as the wind velocity experienced by a given wind turbine experiencing wake effects divided by a wind turbine experiencing free stream wind velocities. The wind velocity deficit results from the model were compared to the measured wind velocity deficits of two different turbines within the Horns Rev wind farm.

The results for comparing the model wake deficits with different wake decay constants of Turbine 17 with the measured data can be seen Figure IV-2 and the results from Turbine 45 in Figure IV-3.

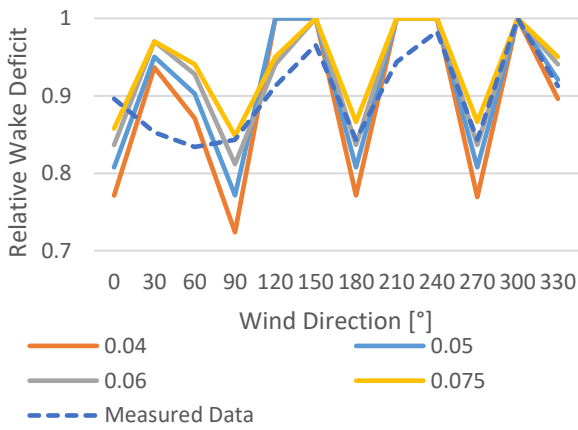


Figure IV-2: Wind Deficit Comparison (Turbine 17)

While analyzing Figure IV-2 and Figure IV-3, the model results show a trend where the highest wake effects occur when the wind approaches from 0°, 90°, 180° and 270°, which is expected with this rectilinear layout. In between these angles the wake deficits at the turbines tested are less, with the model results showing some orientations even experiencing no wake losses.

Between 0° and 90°, the measured data does not trend with the model results as well compared to other orientations. Firstly, the measured wake deficit at 0° is much less than the measured wake deficit for 90°, 180° and 270°. This discrepancy is unexpected, as for example when the wind is approaching from 0°, Turbine 17 is near the back of the wind farm, compared to at 180° Turbine 17 is in the second row.

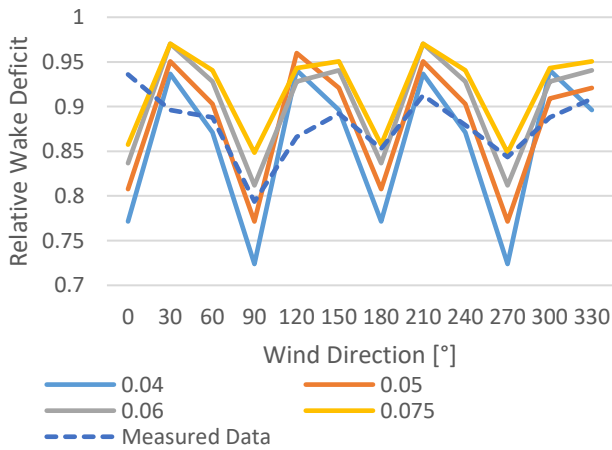


Figure IV-3: Wind Deficit Comparison (Turbine 45)

The model results indicate that Turbine 17 would experience greater wake effects when the wind approaches from 0°, however the measured data does not show this. Additionally, between every 90° the model results indicate a peak where the turbines experience less wake effects, however between 0° and 90°, the measured data show no such peak, although it does show the peak between the other axes. An explanation for why this is more evident for Turbine 17 is that in this orientation, Turbine 17 is near the back of the wind farm and the Jensen model, with a binary approach to partial wakes, may not accurately represent the wake deficits. Additionally, Sorensen [17] indicates that for large wind farm arrays, the Jensen model over estimates the wake effects in the first rows and

underestimates the wake effects in the back rows. This however does not explain the discrepancy for Turbine 45.

With regards to a comparison between wake decay constants, a wake decay constant of 0.075 always underestimates the wake effects, whereas a wake decay constant of 0.04 tends to both over estimate and underestimate depending on the direction of the wind approaching. As expected, the wake decay constants trend in the same order with larger wake decay constants providing lower wake deficit estimates and smaller wake decay constants providing higher wake deficit estimates. There are exceptions to this rule when in some orientations larger wake decay constants have an expansion angle that includes some turbines that the smaller wake decay constants do not (seen at 120°).

1) Limitations in Wind Deficit Validation

The model results do not match the measured data exactly for a number of reasons:

- Including a simplified binary partial wakes function creates larger discrepancies between model results and measured data at certain angles when the measured data shows that certain turbines experience wake losses and the model indicates either much higher wake losses or no wake losses depending on if 50% of the turbine experiences the wake or not.
- A potential influence on the difference between the measured and model results could be attributed to the Weibull distribution parameter assumption for the wind distribution between 7-10 m/s.
- Inconsistencies in the measured data that cannot be explained by relying on second-hand data. Validation with more data would provide more conclusive results.

The wind deficit validation observations indicated that including a partial wake model would most likely increase the accuracy of the model, as would more accurate wind information. Beyond this, further model validation would be valuable with other offshore wind farm data sets which were not available.

B. AEP Validation

When comparing the model AEP results to the measured results for the overall wind farm output, the model was a better predictor than it was for the wind deficit measurements of individual turbines. This was expected as the aim of the Jensen model is to give an estimate of the energy content of a wind farm rather than to describe the velocity field accurately [18].

The AEP was estimated using four different wake decay constants to determine which was the best fit for the measured data. The wake decay constant that fit the measured data the best was 0.04 which gave AEP results within 1% of the approximate AEP that was observed at Horns Rev wind farm in 2005 (the period being tested). A wake decay constant of 0.04 is consistent with the standard value used in wind farm software [17].

Table IV-1: AEP Validation Results

k	AEP (GWh)	Relative AEP
Measured Data	630	100.00%

0.04	626.90	99.5%
0.05	640.50	101.7%
0.06	653.14	103.7%
0.075	665.47	105.6%

C. Model Behaviour Observations

1) Cable Layout Heuristic

The cable layout heuristic was proven to be more effective than the traditional radial design that collects the power from all turbines in a column and transmits it to the substation. A visual comparison of the traditional layout and an improved layout from the cable layout heuristic on a rectilinear wind farm layout can be seen in Figure IV-4.

The heuristic results were compared with traditional designs for different numbers of turbines, different rows and column spacing and different intra-array cable capacities. In all scenarios the heuristic outperformed the traditional design for a rectilinear wind farm layout by a reduction of 11-19% in cable length.

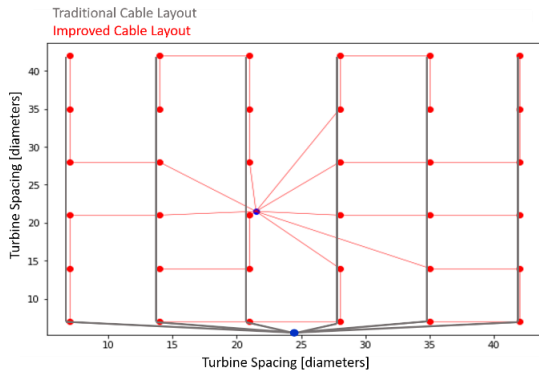


Figure IV-4: Cable layout comparison (rectilinear wind farm layout)

The cable layout heuristic becomes of increased value for non-rectilinear layouts where the function developed for generating the traditional layout struggles to provide reasonable results. Figure IV-5 shows the traditional cable layout function results along with the improved cable layout results. The improved cable layout results in only 68% of the traditional cable length required.

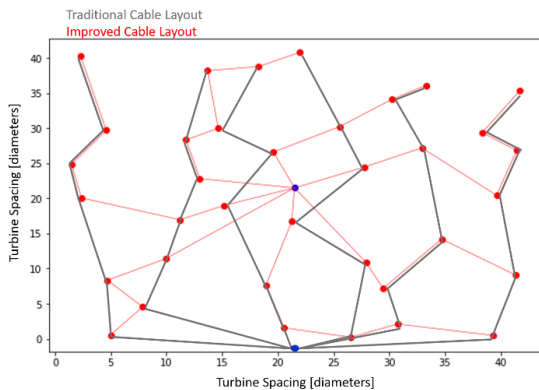


Figure IV-5: Cable layout comparison (irregular wind farm layout)

The cable layout heuristic function consistently provided a cable layout design with shorter overall cable length than the

traditional layout function and was more robust and effective in dealing with non-rectilinear layouts.

2) Wind Rose Sensitivity

Implementation of a binary partial wake model combined with the linear expansion of the Jensen model led to the AEP being very sensitive to small rotations in the wind farm.

When applying a wind rose to a rectilinear wind farm layout there are wind directions where the wakes downstream may “just miss” or “just hit” many turbines in a row, or none at all, creating spikes in AEP for minimal changes in in the orientation of the wind farm as seen in Figure IV-6.

As stated above, a binary approach to a partial shadowing effects was included in the wake model. This results in the hit or miss of a wake being defined by the turbine experiencing more or less than 50% of an upstream wake, which contributes to even larger spikes. To create a smoother AEP response to the wind direction rotation for a rectilinear wind farm layout using

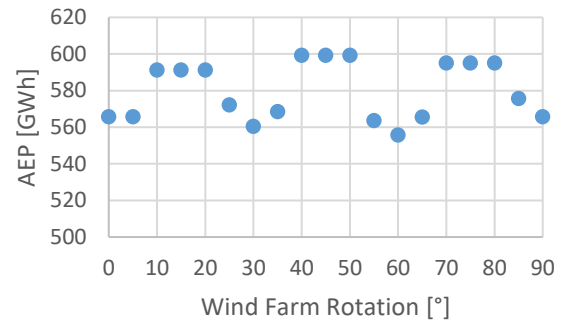


Figure IV-6: AEP sensitivity to wind farm orientation

the Jensen model, a more accurate partial wakes model should be implemented.

A final observation of Figure IV-6 is the 7.8% increase in AEP yield based on a simple change in orientation of the wind farm is why existing wind farms are oriented to an optimal angle with respect to the prevailing winds. This observation lead to the investigation of improving the wind farm layouts further, by removing rectilinear constraints, to increase the AEP and improve the cost effectiveness of offshore wind energy.

V. RESULTS & ANALYSIS

A. Case Study I: Horns Rev Wind Farm

The optimization of the Horns Rev Wind Farm evaluated 900 individual wind farm layouts in total, over 9 generations and determined an optimal layout after the minimum LCOE from 4 consecutive generations averaged a difference of less than 0.0001. It is understood that the limited nature of this optimization simulation does not necessarily provide a true optimum, but these were the best results available due to time restrictions. The existing Horns Rev wind farm is shown in Figure V-1 with a cable layout that was designed using the hybrid cable layout heuristic. The cable layout heuristic was used instead of the installed cable layout to provide a valid comparison between the different wind farm layouts due to assumptions that made in the cable cost sub-model. The improved wind farm layout can be seen in seen in Figure V-2.

Table V-1: Horns Rev wind farm layout comparison

Parameter	Existing Layout	Improved Layout
Cable Length [m]	65611	59943 (91.4%)
Cable Cost [10^6 \$]	38.96	35.59 (91.4%)
AEP [GWh]	626.91	656.37 (104.7%)
LCOE [\$/kWh]	0.0904	.0871 (96.3%)

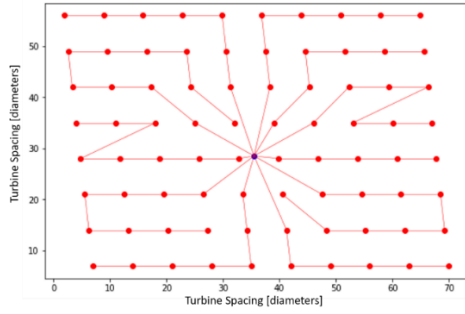


Figure V-1: Existing Horns Rev layout (optimized cable design)

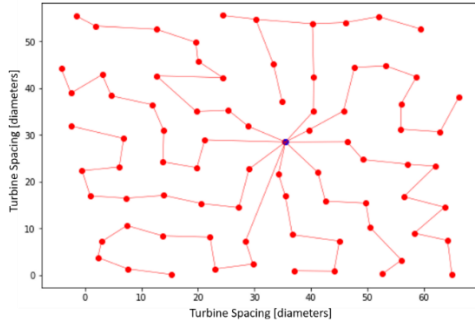


Figure V-2: Optimized Horns Rev wind farm layout

Figure V-2 displays the minimum, average and maximum LCOE value for each generation. None of the individuals that were evaluated resulted in an LCOE as high as the LCOE from the existing layout (0.0904 \$/kWh). If the number of wind farm layouts in the population were to increase, there is a chance that some wind farm layouts would result in an LCOE comparable to the original design. However, from the wind farms evaluated, the result from the existing Horns Rev wind farm layout would be considered an outlier.

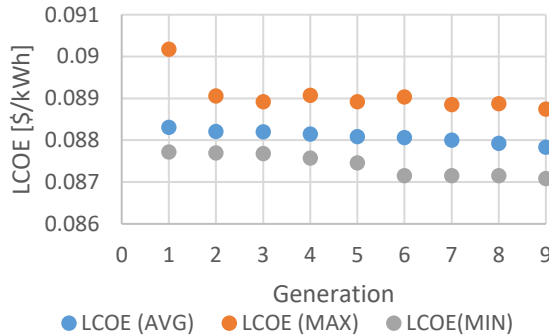


Figure V-3: LCOE evolution of Horns Rev wind farm optimization

The array efficiency for the final design is 90.5% compared to the existing design which was 86.5%. A comparison of the cable length, AEP and LCOE of the two layouts can be seen in Table V-1. The total collection cable length of the improved design is 8.6% shorter than the original layout. The improved design results in an estimated 4.7% increase in AEP. As both the cable length and AEP improve, the resulting LCOE for the improved layout is 3.7% lower than the existing Horns Rev layout.

B. Case Study II: Borssele Wind Farm

The second case study analyzed the Borssele Wind Farm. The Borssele wind farm zone is divided into 5 smaller wind farm sites. Borssele III and Borssele IV are considered for this thesis and will be referred to as the Borssele Wind Farm. What is different about the Borssele wind farm compared to Horns Rev is that the Borssele wind farm has not yet been constructed. So, although an existing design cannot be validated like it was for Horns Rev, the data made available for the design tender [30] is used along with a proposed baseline wind farm design obtained from Perez-Moreno et al. [31] to analyze different layouts. The baseline wind farm layout (seen in Figure V-4) was a rectilinear layout that comprised of 74 5-MW turbines.

Similar to the first case study, the analysis of Borssele wind farm was also limited by time constraints on the optimization. In the case for Borssele wind farm, 600 individual wind farm layouts were evaluated over 6 generations, with the best seen in Figure V-5. The optimization ran for 6 generations before achieving 4 consecutive generations with an average objective function difference of the best layout of 0.0001.

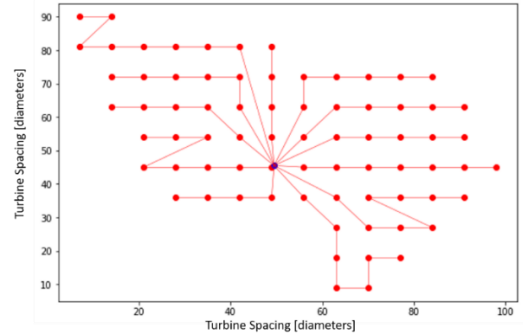


Figure V-4: Baseline Borssele wind farm layout

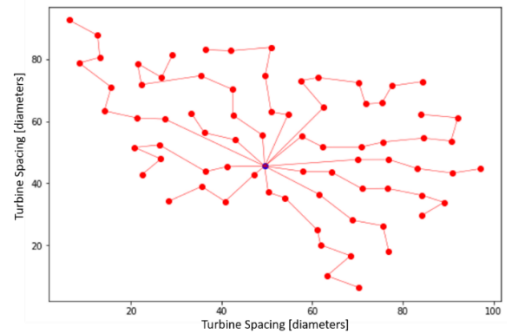


Figure V-5: Optimized Borssele wind farm layout

Figure V-6 shows the minimum, average and maximum LCOE result for each generation, all of which are lower than

the LCOE for the baseline layout (0.0970 \$/kWh). Much like Case Study I, the initial individual simulated was very similar to the baseline layout which is why the maximum value in the first generation is similar to the LCOE of the baseline layout. It should be noted that the LCOE cost for the Borssele wind farm does not consider transmission costs (or losses) because the transmission was provided by another project. Also, the project proposal has a maximum bid for the cost of electricity of 0.11975 €/kWh [30], which indicates that the results from the model are within an appropriate range of expectations.

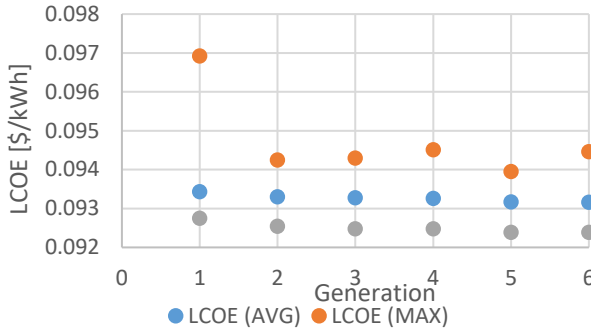


Figure V-6: LCOE evolution of Borssele wind farm optimization

The array efficiency for the final design is 93.0% compared to the existing design which was 87.1%. A comparison of the cable length, AEP and LCOE of the two layouts can be seen in Table V-2. The total collection cable length of the improved design is 3.7% shorter than the baseline layout. The improved design results in an estimated 6.8% increase in AEP. As both the cable length and AEP improve, the resulting LCOE for the improved layout is 4.7% lower than the baseline Borssele rectilinear layout. The influence of each parameter on the LCOE will be explored further in the observations in the following section.

Table V-2: Borssele wind farm layout comparison

Parameter	Existing Layout	Improved Layout
Cable Length (m)	107540	103560 (96.3%)
Cable Cost (10 ⁶ \$)	89.40	86.09 (96.3%)
AEP (GWh)	1411.3	1506.9 (106.8%)
LCOE (\$/kWh)	0.0970	0.0924 (95.3%)

C. Case Study Observations

In both case studies results indicate that optimizing the positions of the individual turbines within the wind farm provides both a higher AEP and lower cable costs. The original expectation was that these two variables were contrasting and that one may have to worsen in order for the other to improve and lower the LCOE. It wasn't considered that both may improve within the optimal layout and as this is the case, at first glance it is difficult to know which variable impacts LCOE more.

However, upon analysis of Figure V-7 and Figure V-8, the average AEP results for each generation trend upwards (improves) as the optimization continues for both wind farms. The average cable cost on the other hand, trends downwards (improves) over generations for Borssele but trends upwards

(worsens) for Horns Rev. This would indicate that in the case of Horns Rev, increasing the AEP was of more influence than lowering cable costs in an effort to minimize the LCOE.

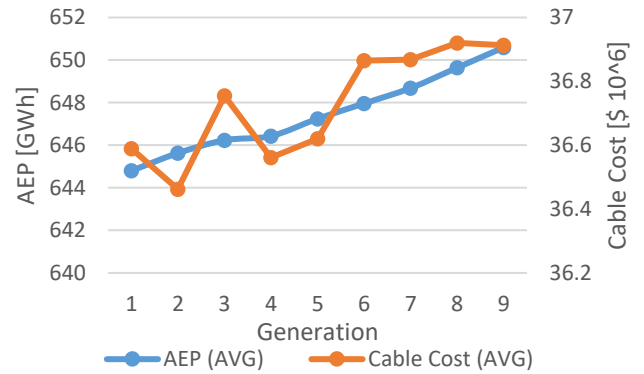


Figure V-7: Horns Rev wind farm – AEP and cable cost evolution

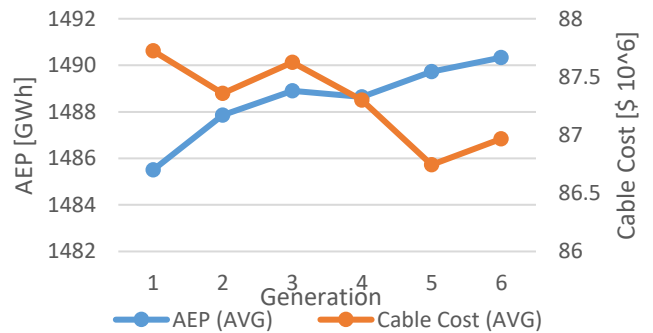


Figure V-8: Borssele wind farm – AEP and cable cost evolution

This relationship can be observed in Equation 1 which shows that the LCOE corresponds to the relationship of the ICC divided by the AEP. As noted above, the intra-array cable costs are only a fraction of the ICC which results in the LCOE being more sensitive to variations in the AEP than the collection cable costs.

The AEP for each wind farm varied no more than 5% once the optimization had abandoned the original rectilinear layout. The cable costs varied much more than the AEP, by 18% and 17% for the Horns Rev and Borssele wind farms respectively. As both the AEP increased and the cable cost decreased for each design relative to the existing layouts, both wind farms saw a decrease in the LCOE which was the expected outcome from the optimization. The optimized layout for Horns Rev experienced a decrease in LCOE of 3.7% and Borssele 4.7%. The difference in the WFLO-driven LCOE decrease between the present work and the results of Pillai et al. [12] may be attributed to the fact that both Horns Rev (80 turbines, 160 MW) and Borssele (74 turbines, 370 MW) are much larger than Middelgrunden (20 turbines, 40 MW) and would experience much more wake interaction. The increased wake interaction and variability for cable design of the larger farms would be expected to provide larger potential for savings if the layout is optimized.

It was evident from the results of two case studies that rectilinear wind farm designs were not optimal with regards to minimizing the LCOE. Despite these findings, which agree

with the prior research, rectilinear wind farm layouts are still the industry standard for offshore wind farms. This may be a result of the industry being conservative in nature and as such, slow to transition away from the traditional designs. As the observations from the thesis indicate that the traditional designs are not optimal from a cost of energy standpoint, they may be considered optimal for other variables, for example easier planning or aesthetics. This trend may change in the future as more accurate models are developed that provide more information on new design strategies to help the industry become more economically viable.

VI. CONCLUSIONS

The objective of the work was to explore the advantages of optimizing the positions of the individual wind turbines within an offshore wind farm. In order to perform analysis on different wind farms, a model was developed that is capable of simulating an existing offshore wind farm by converting external input data into a representative LCOE. The model which outputs LCOE is used in an optimization framework to optimize the positions of the individual turbines within the wind farm with the objective of minimizing the LCOE. Upon consideration of accuracy, availability of data and computing restrictions, the Jensen Wake-deficit Model and a hybrid cable layout heuristic were incorporated into the physical component and the NREL cost scaling model was included into the economic component. A genetic algorithm was selected for the wind farm layout optimization component.

Horns Rev and Borssele wind farms were used as case studies to explore the advantages of optimizing the positions of the individual turbines within an offshore wind farm. The wind farm layout optimization results show that:

- Optimized wind farm layouts resulted in a reduction of collection cable length relative to the baseline rectilinear layout of 8.6% for Horns Rev and 3.7% for Borssele.
- Optimized wind farm layouts resulted in an increase in the Annual Energy Production relative to the baseline rectilinear layout of 4.7% for Horns Rev and 6.8% for Borssele.
- Optimized wind farm layouts resulted in a decrease in the Levelized Cost of Electricity relative to the baseline rectilinear layout of 3.7% for Horns Rev and 4.7% for Borssele.

The initial expectation was that the contrasting nature of the wake effects and the collection cable costs would result in the improvement of one value at the expense of the other that would ultimately lead to an improved LCOE. However, the results from the model indicate that both the wake effects and collection cable costs were improved by applying an optimized layout in both case studies. The LCOE savings were higher than the results of Pillai et al. for Middelgrunden wind farm (1-3.5%). This difference may be explained by the size and shape of the Horns Rev and Borssele wind farms relative to the Middelgrunden wind farm. The larger wind farms studied in this thesis provide increased potential for savings through farm layout optimization layout because of the increased wake interaction and cable design variability.

The results observed from the model in both case studies indicate that there is potential for reducing the levelized cost of electricity for offshore wind farms by optimizing the positions

of individual wind turbines within the layout. However, it is important to consider the assumptions and limitations of the implementation of the model used for analysis.

The following assumptions and limitations should be considered as they relate to the validity of the model and the qualitative results:

- The model was validated against the measured data from one wind farm due to limitations on available data. It is important that the current model is compared with measured data from more wind farms in order to compare the results and determine the model's accuracy.
- The model assumed a 'binary' partial wake effect model which was observed to provide inaccurate wind deficit results with the measured data at certain wind directions.
- The assumption that the foundation costs for each turbine were the same regardless of the bathymetry and soil conditions may cause large discrepancies in the LCOE results. However, the rectilinear constraints are unlikely to provide a better result if the individual turbine foundation costs are considered.

The subsequent assumptions and limitations should be considered as they relate to the accuracy of the model and the quantitative results:

- The optimization framework was constrained by time which limited the effectiveness of the application of the genetic algorithm. Using a more powerful computing device and having longer simulation times would allow for improved optimization results.
- The accuracy of the LCOE results are limited by the uncertainty of the input values incorporated into the economic model which vary based on the existing market and wind farm location. This is less relevant for relative comparisons, however could provide increased value by having the model LCOE be representative of the actual wind farm LCOE.
- The application of a simplified cable loss sub-model provides limited accuracy for the total electrical losses experienced in the collection cable network. However, in both case studies the cable length was reduced relative to the existing layout, therefore it is expected that improving this sub-model would result in increased value for optimizing the turbine locations.

Despite the limitations and assumptions, the results still provide valuable insight into the benefits of wind farm layout optimization as the same parameters and conditions were applied to each simulation.

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