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Offshore Wind Farm Layout Optimization—State of the Art

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Offshore Wind is one of the most promising renewable energy sources, but the cost is still too high to be competitive. Optimizing the layout of a wind farm may help to improve the competitiveness, but it presents a significant engineering challenge. This paper presents the state of the art of offshore wind farm layout and identifies the main criteria used for its optimization with respect to a number of parameters such as the cost of energy and annual energy production. Used methodologies in farm design, as well as key aspects of a wind farm that are subject to optimization, will be analyzed. Available commercial software for wind farm design will also be presented and characterized and their limitations identified. The paper concludes with suggestions for further investigation.

INTRODUCTION

Wind energy has been one of the main and fastest-growing sources of renewable energy and has contributed significantly to the decarbonization of the electric sector. Onshore wind has been the main contributor to this growth with a yearly average growth rate of 15.6% between 1996 and 2011 and with more than 96 GW installed just in Europe (Wilkes et al., 2012).

The first offshore wind farms were installed in the late 90s in Northern Europe in shallow waters (5 to 10-m deep) and were using monopiles. This type of solution is now commercial and represents a 9.2% share of the total installed capacity (Wilkes et al., 2012). More recent deployments show a trend to move further away from the coast and into deeper waters (up to 35 m). Although offshore wind is more complex and costly than onshore wind, both in deployment and maintenance, significantly higher energy yields are expected due to the higher intensity and persistency of winds further offshore. The goal is to make offshore wind competitive with other alternative energy production technologies, including conventional technologies, i.e., achieve a Cost of Energy (CoE) lower than 100 €/MWh. Therefore, it is important to understand the offshore wind energy cost structure in order to control it and make a competitive business case.

During the last decade, significant effort was applied in understanding onshore wind and maximizing energy extraction from wind. In what concerns farm design, most of the effort was applied in micro-sitting the wind turbines and in characterizing how the topology of the terrain interacts with the wind and its impact on the turbine performance. Therefore, in most of the cases, the layout optimization of such wind farms only considers maximizing the Annual Energy Production (AEP) (Gu and Ji, 2010). The same optimization criterion was used for the early years of offshore wind, where the wake effect was the main effect that was taken into account in the definition of an offshore wind farm layout (Rivas, 2007).

As the wind farms started being installed in lower wind sites or going offshore further away from the coast or into deeper waters, other concerns were raised. The complexity of installing a wind farm increased significantly, so maximizing the AEP was not enough to make a competitive business case. The wind farm layout is a key element in the profitability of a project, so more complex optimization approaches were developed.

This paper will first characterize the offshore wind farm main cost drivers and identify what impacts the CoE. The next section introduces the aspects and components of a wind farm that affect its cost and that can be subjected to optimization. Several optimization algorithms are presented. The wind farm layout optimization's state of the art is reviewed, and the commercially available software is identified and characterized. Finally, a set of conclusions is presented.

OFFSHORE WIND FARMS COSTS

Offshore wind farms started to be developed in the late 90s, Middelgrunden in Denmark being one of the pioneer projects in this sector. The first wind farms were installed in shallow waters (less than 20-meter water depths) and relatively close to the coast.

More recently, a trend has been seen to move offshore wind farms further away from the coast and into deeper waters. As an example, the Beatrice Offshore Wind Farm is located 25 km off the east coast of Scotland in 45-meter water depths, and the WindFloat and Hywind floating wind turbine prototypes are installed in 50-m and 120-m water depths in Portugal and Norway, respectively (Roddier et al., 2010). But this trend imposes increased challenges in terms of costs, O&M (operation and maintenance) and logistics.

Capital Cost

By nature, offshore wind farms are more expensive than onshore wind farms. As can be seen in Table 1, the total wind turbine cost

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KEY WORDS: Offshore, wind, energy, layout, optimization, algorithm, cost.

	Offshore share of total cost [%]	Onshore share of total cost [%]
Wind turbine	44	64
Foundation	16	7
Electrical infrastructure	17	10
Installation	13	11
Planning & development	10	8
Total cost [M€]	3.270	1.227

Table 1 Capital structure of fixed foundation offshore and onshore wind farm (Krohn et al, 2009)

share in fixed-foundation offshore wind farms is only 44%, while in onshore wind farms, it has a cost share of 64%. In contrast, the electrical installation, foundation and installation gain relevance in the total cost share. The higher cost of offshore wind farms and the redistribution of cost share demonstrate the increased complexity of an offshore installation.

The foundation is generally more complex in design and installation. It is very dependent on the meta-ocean conditions, seabed characteristics and water depths found at the site. Typical types of foundations can be monopile, tripile, gravity base, jacket or, more recently, floating solutions.

The installation is also more complex offshore than onshore. Most of the foundations require drilling and pilling to fix the foundation to the seabed, which requires dedicated vessels. Exceptions to drilling and pilling are the gravity base and floating foundations that only require seabed preparation or deployment of anchors, respectively. To complete the installation, a dedicated heavy-lift vessel is also required to install the nacelle on top of the tower. These types of vessels only operate in very strict sea conditions, and their costs are very high. Some floating foundations may not require the need of heavy-lift vessels if their draft is sufficiently small to allow the structure and turbine to be fully assembled onshore. The power transmission requires the installation of electrical cables on the seabed from the wind farm to shore. Inter-array cabling also needs to be installed using proper vessels.

Going offshore also brings some benefits, as it allows using bigger turbines with rated power higher than 3 MW, which is the current limit of onshore wind farms due to transportation limitations. The increase in turbines' rated power will be extremely important for the economical feasibility of offshore wind farms, as this will allow spreading the high fixed costs (such as installation of power transmission cable, substation and even the foundation of the turbines) over more energy produced, thus reducing the total CoE.

Cost of Energy

The CoE is defined as the cost per unit of energy produced [€/kWh], i.e., a measurement of the balance between the cost and the energy produced by a power production unit (in this case, a wind farm). The CoE is defined as:

$$CoE = \frac{\sum_{n=0}^{N} \frac{Inv + C_{O\&M} + C_{others}}{(1+a)^n}}{\sum_{n=0}^{N} \frac{AEP}{(1+a)^n}} \tag{1}$$

where Inv is the annual investment [€], $C_{O\&M}$ is the cost of operation and maintenance [€], C_{others} is other costs during the lifetime of the project, a is the discount rate [%], AEP is the annual energy production [kWh] and N is the lifetime of the project [years].

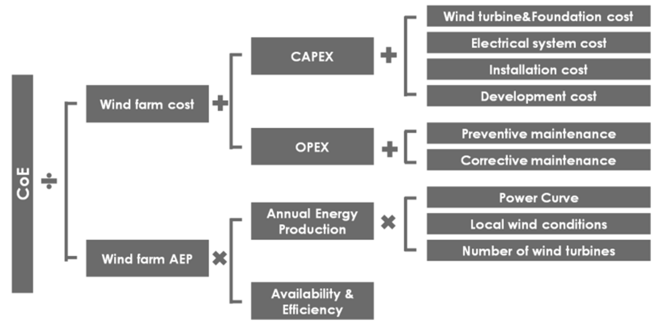

Fig. 1 CoE relational tree

The CoE can also be represented by the relational tree illustrated in Fig. 1.

On the one hand, the wind farm costs result from the addition of the capital expenditure (CAPEX) with the operational expenditure (OPEX). From the experience in Denmark (Risø DTU), it is estimated that the OPEX can have an impact of between 17% and 30% in the CoE (Engels et al., 2009). According to the experience in UK Round 1 (Feng et al., 2010), the OPEX is, on average, 18% of the CoE, while some early models assumed 25%–30% of the CoE (Marsh, 2007).

On the other hand, the energy cost is directly affected by the wind farm annual energy production, which mostly depends on the individual turbines' characteristics and on the local wind conditions. The energy produced is also very dependent on the availability of the wind turbines (reliability and accessibility are two important factors on this) and losses, in particular transmission losses and wake losses.

All these factors must be taken into account at an early stage of the design of a wind farm in order to reduce the CoE. The CoE is the variable that is used to represent the efficiency of a project as a whole. Other financial parameters (IRR, NPV, etc.) are also important when deciding whether or not a project is economically feasible.

OPTIMIZATION OF AN OFFSHORE WIND FARM

As described in the previous chapters, the cost and performance of a wind farm are affected by multiple factors. The layout of a wind farm may be optimized based on several criteria. The most commonly used consists of micro-sitting the wind turbines to maximize the extraction of energy of the whole wind farm by reducing the aerodynamic interference between wind turbines.

Considering the increased challenge of going offshore, the promoter faces a significant challenge in maximizing the energy extraction at the lowest CAPEX and OPEX during the lifetime of the wind farm within a range of financial, safety and environmental constraints, which is equivalent to identifying the global minimum of the CoE.

This leads to a complex and multidisciplinary engineering challenge, which consists of identifying the global optimal solution for the following set of variables:

– Turbine selection: The turbine selection will have direct a impact on the CAPEX as well as in the energy production. The turbine will also be the most critical component that will drive the availability and reliability of the wind farm. It is important to model accurately these characteristics of the wind turbines.

– Foundation selection: The foundation is a passive component but also relevant in terms of CAPEX. Its characteristics will depend on the turbine size, soil characteristics and water depth.

– Electrical infrastructure: The electrical infrastructure includes the inter-array cabling, the transmission cable and the offshore substation. The electrical infrastructure needs to be properly designed to allow redundancy and increase availability at the lowest cost possible. Losses in the inter-array and transmission system can account for up to 3-5% of the energy produced.

– Micro-sitting of wind turbines: One of the factors that most influences the performance of wind turbines is the wake effect. Therefore, a proper positioning needs to be engineered. The position of the turbines will also have a direct impact on the foundation and electrical infrastructure.

– Operation and maintenance (O&M): A critical component in offshore wind farms is O&M, which normally tends to assume approximately 20% of the total CoE. The O&M is directly influenced by the size, availability, reliability and accessibility of the wind farm. The wind farm (especially the wind turbines) needs to be properly modeled to understand their failure rates, and an adequate O&M strategy and logistics need to be established to reduce O&M costs and wind farm downtime.

OPTIMIZATION ALGORITHMS

Generally, optimization algorithms can be divided into two basic categories: determinist and probabilistic. Determinist algorithms are mostly used when there is a clear relation between the possible solutions and the utility function for a given problem. In this case, the search space can be efficiently explored to achieve the optimal solution. On the other hand, if the utility function is complex, the search space is very big, or the number of variables that influence the solution is high, then it becomes hard to solve the problem using a determinist approach. Using a determinist algorithm would result in a very time-consuming process and, in most of the cases, would not be feasible. Probabilistic algorithms appear as an alternative for these complex cases. The layout optimization configures as a complex problem; therefore, probabilistic algorithms are the best approach to solve this problem.

The present section will describe some of the most used optimization algorithms to solve layout optimization problems.

Genetic Algorithm

Genetic algorithms are robust optimization techniques based on the process of natural selection and evolutionary genetics. An initial population of candidates is selected (individuals) over the entire search space (entire range of possible solutions), and the algorithm will search for the most fit individuals. As the most fit individuals are more likely to reproduce, they will pass their genetic information to the next generation. As the process continues, the better genes will dominate, and the solution will tend to the optimum solution. The new generation is created using three operations: selection, crossover and mutation. In selection, the most fit individuals are selected from the population so that they can combine their genetic information to create the next generation. The crossover operation consists of combining the best qualities of the individuals to create the next generation, which increases the mean fitness of the population. The mutation operation allows random alterations to individuals, which allows continuing the exploration of the search space for the global optimum solution (Eiben et al, 1994.).

Evolutionary Strategy

Like the genetic algorithm, the evolutionary strategy algorithm is also based on the process of natural selection. An initial population is selected within the search space, and the next generation is created by applying mutations and selection operations. The mutation is performed by adding a normal distributed random value to each vector component. In the selection operation, the most fit individuals are selected to generate others, but they are selected based on the fitness ranking and not on the actual fitness values.

A variant of the evolutionary algorithm is the covariance matrix adaptation evolutionary strategy (CMA-ES) algorithm, which allows the algorithm to respect the correlations between the variables. The creation of new generations will continue until the defined criteria are met (Hansen et al., 1995).

Ant Colony System

The ant colony system was inspired by real behavior of ants. Ants are capable of finding the shortest path from a food source to their nest without using visual cues by exploiting pheromone information. While walking, ants deposit pheromones on the ground and follow pheromones previously deposited by other ants.

The behavior presented inspired a search algorithm to find the optimal path to reach a destination. Any system that can be represented with a graph can use this algorithm to find the optimal solution or the shortest path or the path with the lowest cost. The algorithm consists of having a set of ants that search in parallel for good solutions. Each ant constructs a solution in an iterative way and deposits pheromones on each path by exploiting information created in the past by previous ants. After several ants, the better path will be identified and will be chosen by other ants (Dorigo and Gambardella, 1997).

Particle Swarm Optimization Algorithm

Particle swarm optimization was introduced by Kennedy and Eberhart (1995). It was inspired by social behavior of fish schooling and bird flocking. The particle swarm optimization algorithm works by having a population (called a swarm) of candidate solutions (called particles). These particles are moved around in the search-space. The movements of the particles are guided by their own best-known position in the search-space as well as the entire swarm's best-known position. When improved positions are being discovered, these will then come to guide the movements of the swarm. The process is repeated, and by doing so, it is hoped, but not guaranteed, that a satisfactory solution will eventually be discovered (Kennedy and Eberhart, 1995).

STATE OF THE ART AND METHODOLOGY REVIEW

The literature of the last decade was reviewed to characterize the state of the art of layout optimization of an offshore wind farm. The research effort has been mainly focused on identifying the solution leading to minimum wake interaction with downstream turbines in order to minimize its effect on the whole wind farm. Significant work has been done in this area since the early 2000s (Ituarte-Villarreal and Espiritu, 2009).

Later studies started also to focus on the optimization of other aspects of wind farms, such as the electrical connection (inter-array connection and power transmission onshore), trying to identify the optimal solution to increase availability and reduce power losses at the lowest cost possible. More recently, further work has begun in modeling and understanding the O&M of an offshore wind farm, as it was identified as a relevant component of the CoE.

Due to the complexity of finding the optimal layout of a wind farm, bio-inspired algorithms, such as evolutionary strategies, genetic algorithms and particle swarm optimization, have been used in this complex problem (Wagner et al., 2011).

The following sub-sections will cover the work developed in optimizing the layout of a wind farm, taking into account the wake effect, electrical connection, O&M and other multiple factors.

Wake Effect

Wake effect has been one of the main drivers for layout optimization in recent years. Wan et al. (2009) mentioned that the systematic approach to wind turbine placement was first proposed by Mosetti et al. (1994) and improved by Grady et al. (2005), using genetic algorithms with favorable results, but using simple models for the wind distribution and power evaluation. Wan et al. (2009) proposed a more realistic modeling of the wind conditions, using a binary-encoded genetic algorithm, and demonstrated that the wind turbine placement can be improved, even using half of the population that Grady et al. used, which means that the approach proposed is less demanding of computational time. However, the wind direction was not fully taken into consideration in these optimization models.

Rasuo and Bengin (2010) noted that Genetic Algorithms are a very powerful optimization method and that they have been applied successfully in many complex applications, but the applications used for wind turbine positioning assume that wind turbines can only be located in discrete positions defined by a grid. Based on that, they decided to introduce several improvements in the fitness function and to allow the wind turbines to be adjusted freely instead of being located in the center of each cell of the defined grid, so that the wake effect could be minimized. This method proved to be successfully applied in defining the optimum layout of a turbine; thus, it is a very time-consuming algorithm if more turbines or a more complex model are incorporated.

Kusiak and Song (2010) proposed a methodology to define a wind farm layout for maximum wind energy capture. To accomplish that objective, a multi-objective evolutionary strategy algorithm considering wake losses and wind farm radius and turbine distance constraints was used, thus replicating an industrial application more realistically. This approach allows defining the optimal solution while satisfying all constraints set; thus, it defines the maximum number of turbines allowed in a wind farm, while other approaches optimize the layout given the number of wind turbines.

All the algorithms and work presented allow finding a good solution (local optimal solution), but none of them can indicate how far away it is from the global optimal solution. With this in mind, Wan et al. (2010) proposed an improved algorithm to increase the probability of getting better solutions, namely, the Particle Swarm Optimization algorithm with Gaussian mutations (GPSO) to solve constrained optimization problems. These authors introduced two Gaussian mutations operators to allow jumping from local optimum solutions to other, better solutions. The authors demonstrated, using three benchmark problems (Himmelblau's problem, welded beam design problem and the pressure vessel design problem), that GPSO achieved the best performance and proved to be more accurate, robust and efficient in terms of locating the global optima when compared with alternative algorithms.

For Wagner et al. (2011), the motivation was primarily related to the complexity of defining the optimum layout of hundreds of turbines. Based on the work of Kusiak and Song (2010) that used an evolutionary strategy to define the layout of a few turbines, Wagner et al. (2011) expanded the work for the placement of several turbines, taking into account the interactions between different turbines. To achieve this target, the authors proposed the Covariance Matrix Adaptation-based evolution strategy (CMA-ES), which allows the algorithm to respect the correlations between the variables, making it a powerful evolutionary algorithm. Wagner et al. (2011) was able to demonstrate, with satisfactory results, the layout optimization problem with up to 1000 turbines.

Electrical Connection

Several authors investigated the optimal design of inter-array and transmission cabling design and optimization of the number and location of the substations in order to reduce CAPEX, increase reliability of the system and minimize cost of ownership by reducing electrical losses (Hopewell et al., 2006).

Hopewell et al. (2006) defined a methodology to optimize the turbine layout, location of offshore substations and the sizing and design of electrical cabling. The authors use a simple technique developed by a company called SKM (www.globalskm.com) to optimize the location of the transformer platform with respect to reducing the length of the inter-array cabling between the turbines and the substation. They also explored how to size equipment, taking into account economic aspects. Although they state that cables with larger sections are more expensive, it can be shown that larger cables can be worth it, as losses are significantly lower over the project lifetime.

Zhao et al. (2006) proposed a heuristic method to optimize the electrical system design. The chosen method was the Genetic Algorithm using different techniques, and the objective was to optimize the CoE and reliability of the system. The algorithm considered the number of clusters, voltage level for the inter-array cabling and for the transmission, and the existence of offshore substation as optimization variables. The algorithm was tested in a real wind farm layout with 30 turbines. The author identified the premature convergence as the main problem of the Genetic Algorithm and therefore implemented different techniques to overcome this issue. Although all the techniques used could achieve the optimal design, there was one in particular that had better results but was computationally more demanding.

Wu et al. (2012) used a Genetic Algorithm to optimize the wind farm layout based on the wake effect and used an Ant Colony System to optimize the electrical system design. This was one of the few approaches found in the literature that consider two different criteria that contradict each other, as the turbines must be as far away as possible from each other to reduce the wake effect and, to reduce the cost and losses in the electrical cabling, the turbines should be as close as possible. The authors follow an approach that separates the two problems. First, they use the Genetic Algorithm to define the optimal layout of the wind farm and subsequently use the Ant Colony System to optimize the electrical system. This approach takes advantage of the wake effect being dominant over the losses of the electrical system and does not find the wind farm's optimal layout. Further investigation could be done to understand the benefit of optimizing the wake effect and electrical system design jointly.

Lumbreras and Ramos (2012) stated that an optimal system includes redundant elements and might deviate from the standard electrical configurations (radial, single or double-sided ring, star and multi-ring). The focus of the authors was to formulate a methodology to define the optimum electrical system configuration, demanding fewer computational requirements and achieving significant time savings. The algorithm used was a Mixed Integer Programming taking benefit of decomposition strategies, namely, Bender's decomposition (see Benders (1962) for further details) and Progressive Contingency Incorporation (proposed by the authors). The authors were able to achieve two orders of magnitude in time savings.

Operation and Maintenance

Operation and maintenance (O&M) is a complex activity with several interactions and implications in the performance of the wind farm. O&M does not have a direct impact on the layout of the wind farm but is a relevant component in the CoE, thus it must be considered when planning a wind farm. Therefore, to set up a proper O&M strategy, it is necessary to model and manage the supply chain, maintenance crew and vessels and all the logistics involved. Accessibility is also critical and must be considered in the modeling. The O&M can be considered as preventive maintenance, corrective maintenance and major overhauls. Each of these has its specificities: preventive maintenance considers all periodic maintenance that is scheduled to inspect or replace consumables or components of a device. Corrective maintenance is an activity that normally is not scheduled or expected and requires human intervention to identify, isolate and repair the failed component. Major overhaul maintenance falls in the category of corrective maintenance activity but with high complexity and normally requires the mobilization of a dedicated infrastructure. The corrective maintenance is the O&M activity most impacted by the accessibility to the wind farm and leading to lower availabilities of the turbines.

The Energy Research Centre of the Netherlands (ECN) has been interested in understanding the impact of the O&M activities and optimizing it. This led to the creation of two tools to better estimate the O&M costs during the lifetime of the project (Eecen et al., 2007). The first tool, O&M Cost Model, was developed to estimate the long-term averaged O&M costs based on historical generic data. The second tool, O&M Cost Estimator (OMCE), uses the wind farm data to estimate and update the time-varying O&M costs during the operation phase of the project, using a model that represents the installed turbines as well as their failure rate. This tool definitely provides an improvement in the O&M cost estimation but does not provide an optimized O&M strategy.

Further literature review demonstrated that the number of unplanned repairs increases and can reach between 50%–70% of all O&M tasks if no O&M strategy is in place, leading to high costs (Bussel, 1997). Both Kooijman et al. (2004) and Andrawus et al. (2007) stated that the O&M strategy followed in the North Sea offshore wind farms based on corrective maintenance has led to over-maintenance strategies. The authors agree that an improved O&M strategy based on preventive maintenance will result in increased reliability of equipment, resulting in lower O&M costs.

Other authors proposed that the O&M activities should follow a risk-based approach (Sorensen, 2009) or even a preventive maintenance strategy (Hau, 2006)

The summary above makes clear that no optimum O&M strategy has been found so far, and several options are still being considered. There is a need to further investigate the O&M activities in order to define the best approach to reduce cost and increase the reliability of the wind farm. In their analyses, the authors reviewed have neglected the impact of the supply chain, logistics and transportation means to the offshore site.

Multiple Factors Optimization Approach

Very few approaches were found in the literature focusing on more than one factor to optimize the layout of the wind farm. Most times, the factors are isolated and also treated individually because of the complexity of solving a multi-criteria optimization problem. However, there are several factors that have correlation between them and affect the layout of the wind farm in different ways. Elkinton et al. (2005) launched a project called Offshore Wind Farm Layout Optimization (OWFLO) with the purpose of developing an integrated approach where several factors were taken into account in the layout definition. Thus, the project considers the wake effect, component cost models, operation and maintenance, availability and electrical system design as relevant factors for layout optimization leading to minimum CoE and maximum energy production. The main objective of the project was to build a modular tool dealing with all the factors referred to above, using state-of-the-art models available in the literature and adapted, when necessary, to provide the wind farm optimal layout (Fig. 2).

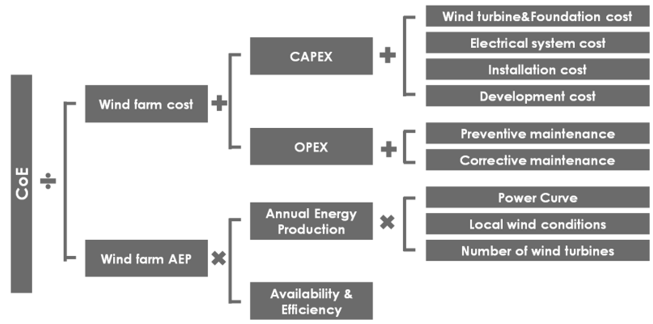

Fig. 2 Modular structure of the tool developed in the OWFLO project (Elkinton et al., 2005)

COMMERCIAL SOFTWARE FOR LAYOUT OPTIMIZATION

There are several wind farm optimization commercial software available, including OpenWind, provided by AWS True Power, WindFarmer, provided by GL Garrad Hassan, WindFarm, provided by ReSoft, and WindPro, provided by EMD. The commercial software are built with modules focusing on different aspects, as can be seen in Table 2.

From the analysis of the capabilities of the commercial software, it was found that only a few are focused on optimizing the layout of the wind farm by reducing the wake effects. Other factors, such as the electrical system, tend to be neglected. Instead, the commercial software is more focused on analyzing the performance of the wind farm, given the design and specifications.

	OpenWind AWS True Power	WindFarmer GL Garrad Hassan	WindFarm ReSoft	WindPro EMD
Energy yield calculation	•	•	•	•
Advanced wake effect models	•	•	•	•
Cost analysis		•		•
Site restrictions	•	•		•
Optimization				
Layout based on CoE	•		•	
Layout based on AEP		•	•	•
Electrical system		(1)		•
Noise	•	•	•	•

(1) WindFarmer from GL Garrad Hassan allows designing the electrical system but does not optimize it.

Table 2 Capabilities of the commercially available software for wind farm layout optimization

CONCLUSIONS

The present work reviews the state of the art of methodologies and commercial software available for offshore wind farm layout design. It was identified that optimizing the layout is a critical area of the design of an offshore wind farm and definitely will contribute to reducing the CoE, improving the business case of the project.

Several criteria to optimize the layout were used by different authors, such as maximizing the AEP or minimizing the CoE. From the review, it was clear that, due to the complexity of an offshore wind farm, minimizing the CoE is the criterion that best improves the business case, because it takes into consideration both the factors that impact the cost during the lifetime of the project and the energy production. Most of the approaches reviewed only optimize the CoE based on one individual factor, e.g., the wake effect or electrical connection or O&M. Only one approach with an integrated view was found in the literature: the OWFLO project (Elkinton et al., 2005). Regarding the optimization of a wind farm based on wake effect, it was understood that the existing algorithms can achieve good results, but their results can be improved towards a more optimal layout by including more realistic restrictions and models. Further work needs to be developed in this area to quantify the benefits of adding such complexity. Regarding the optimization based on the electrical system design, there was no reference or study on the ideal size of the wind farm in order to minimize the fixed cost of this infrastructure and its impact on the CoE. Also, there was not found in the literature an integrated approach where the wake effect and the electrical system design are optimized at the same time. While the minimization of the wake effect required the turbines to be spaced apart to reduce costs and electrical losses, the turbines should be as close as possible to each other. Despite the increased computational complexity, it would be interesting to understand if relevant CoE reduction is achieved by this joint optimization.

The state of the art of O&M modeling and optimization was also reviewed, and it was found that no optimum strategy was achieved yet and that the current models neglect the impact of the supply chain, logistics and transportation means to the offshore site.

The available commercial software was also reviewed, and it was identified that they are not focused on the layout optimization of the whole wind farm.

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