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Optimal wind-turbine micro-siting of offshore wind farms: A grid-like layout approach

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HIGHLIGHTS

- A novel approach to optimize grid-like layouts of offshore wind farms is presented.
- A new approach is proposed to handle realistic constraints on maximum occupied area.
- Several improvements and measures to prevent premature convergence are proposed.
- The behavior of genetic algorithm and particle swarm optimization is compared.
- The layout of a real project, the Horns Rev 3 OWF, is optimized considering publicly available data.

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ABSTRACT

This paper presents a new approach for the optimization of the layout of offshore wind farms. Almost all previous work on optimal micro-siting for large offshore wind farms have been based on irregular arrangements of wind turbines. However, most offshore wind farms already built are configured in symmetrical/regular layouts. From a mathematical point of view, the geometrical relationships of such symmetrical layouts enable the problem to be defined by just a few variables. This presents a considerable advantage compared with irregular arrangements where the number of variables is directly linked to both the number of wind turbines and the number of cells in which the computational domain is discretized. In contrast, symmetrical layouts are more demanding with regard to the optimization process, since the problem constraints, such as the shape of the available exploration area to deploy the project, the maximum surface allowed, and the maximum number of wind turbines, drastically increase the non-linearity of the objective function, which affects the ability of the optimization algorithm to achieve the optimal solution. This work compares the behaviour of two meta-heuristic optimization algorithms (the Genetic Algorithm and Particle Swarm Optimization) in solving the addressed problem and, more importantly, it introduces a series of improvements on the objective function, which enhance the behaviour of the optimization algorithms when dealing with realistic constraints, such as the shape of the concession zone and maximum deployable area. Finally, the performance of the proposed methodologies has been tested under two situations. The first scenario is a small-sized hypothetical offshore wind farm. In the second scenario, the layout of a real project (Horns Rev 3 offshore wind farm) has been optimized and compared with the solutions proposed by the Danish transmission system operator. The results obtained show the ability of the proposed tools to successfully show the ability of the proposed tools to optimize offshore wind farms under realistic considerations.

1. Introduction

By the end of 2016, the worldwide cumulative offshore wind capacity was 14.38 GW (2.22 GW of which being new capacity installed during 2016) [1]. Even though offshore wind technology is not as mature as that onshore, it is considered a strategic

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technology for the replacement of conventional fuel-based sources for the generation of electricity.

In the European Union, offshore wind energy is expected to play a major role in achieving the targets for the year 2020, which specify at least a 20% renewable energy share in final energy, with a planned capacity, according to the National Renewable Energy Action Plans (NREAP), of 43.9 GW by 2020 [2].

At present, the largest operational offshore wind farm (OWF) is the London Array I Wind Farm in the United Kingdom, with 175 wind turbines (WTs) of 3.6 MW each and an overall rated power of 630 MW. Fig. 1 shows the grid-like layout of the wind turbines used in the London Array I wind farm and that of the Sheringham Shoal wind farm, along with the concession areas granted to develop each project [3].

Symmetrical layouts have been proven to be less efficient in terms of energy yield than irregular layouts [4]. However, regular layouts are usually employed (with certain exceptions) in operational offshore wind farms. The application of symmetrical layouts in commercial offshore wind farms is due to two main reasons: (i) reducing the visual impact in the case of near-shore wind projects; and (ii) ensuring the navigability of the area (not only for the activities of fisheries but also to facilitate operations and maintenance tasks).

The problem for optimal micro-siting of wind turbines in onshore/offshore wind farms has been widely studied in the existing literature. In broad terms, there have been two main lines of research into this topic: (i) the development/application of new or alternative optimization methods; and (ii) the analysis and proposal of wind farm models of a more realistic nature concerning several aspects such as the economic performance of the project, costs, energy losses, risks and uncertainty, and environmental/regulatory issues. The authors would like to refer to [5,6] for a thorough literature review on the optimal wind-farm design problem. In addition to the work presented within these two reviews, there are also several other relevant studies that are worth analysing.

Regarding optimization techniques applied to the micro-siting problem, genetic algorithms (GAs) have been used in several studies to optimize the position of wind turbines. In 2005, Grady et al. [7] proposed the minimization of the levelized cost of energy by a simplified economic model based on economies of scale. A similar approach was proposed in 2010 by Serrano et al. [8] by maximizing the net present value of the project for onshore wind farms. This approach was further improved and particularized to offshore facilities by introducing a new economic model [9]. In 2010, Sisbot et al. [10] suggested a multi-objective GA applied to a case study on the island of Gökçeada in Turkey. In 2013, Chen et al. [11] proposed the optimization of a wind farm through GAs by considering the economic model presented by Grady and including different hub heights. A case study for an offshore wind farm, in Hong Kong, optimized by a multi-population genetic algorithm was presented in 2015 by Gao et al. in [12]. The following year, Hamdam and Abderrazzaq [13] proposed a GA to optimize small wind turbines. An enhanced genetic algorithm combined with simulation optimization was proposed in 2017 by Yin et al. [14]. Particle swarm optimization (PSO) algorithms have also been widely used in the wind turbine micro-siting problem. In 2010, Wan et al. [15] proposed a PSO algorithm to optimize the location of wind turbines by considering a continuous computational domain. This work was further improved in 2012 by including a local search strategy [16]. In the same year, Chowdhury et al. [17] introduced a PSO algorithm to optimize the location of wind turbines and considered varying wind conditions over the area under study. Hou et al. [18] proposed a PSO to optimize an offshore wind farm in 2015 by taking a discretized computational domain into consideration. In 2016, Pookpunt and Ongsakul analysed a case study in the Huasai district in Thailand by means of the binary particle swarm optimization algorithm [19]. Other optimization techniques have also been proposed for the optimization of the layout of wind turbines: Park and Law tackled the maximization of power production by sequential convex programming [20]; Guirguis et al. proposed non-linear mathematical programming based on gradient information [21]; Rehman et al. introduced a Cuckoo Search Algorithm in [22]; Mittal et al. [23] proposed a hybrid optimization method by combining a GA and gradient search; Mayo and Daoud presented an Informed Mutation Operator algorithm to maximize the energy production of wind farms in [24]. A two-step optimization process was presented by Perez et al. [25] to maximize the annual energy production (AEP) of offshore wind farms by first using a heuristic

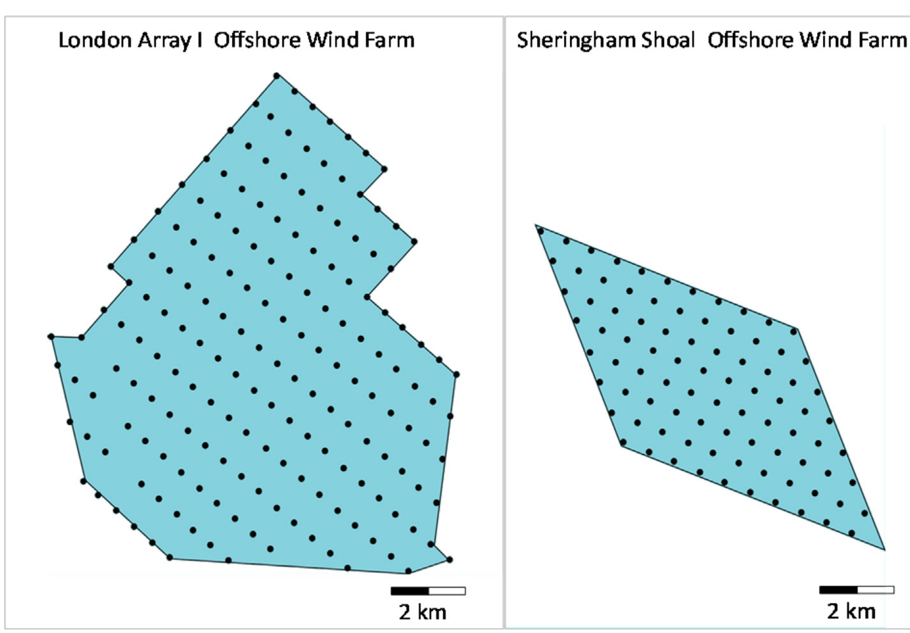

Fig. 1. Example of symmetrical layouts used in operating offshore wind farms: London Array I Offshore Wind Farm (left-hand side) and Sheringham Shoal Offshore Wind Farm (right-hand side).