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Optimal design of neighbouring offshore wind farms: A co-evolutionary approach

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HIGHLIGHTS

- A novel methodology to optimize neighbouring offshore wind farms is presented.
- A co-evolutionary algorithm is proposed to find an optimum Nash equilibrium solution.
- The equilibrium solution considers the design options of other neighbouring projects.
- Non-cooperative and cooperative approaches are compared to classical methods.

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ABSTRACT

This paper presents a new approach for the optimization of neighbouring offshore wind farms. Offshore wind energy is one of the most promising and developed low-carbon generation technologies. However, the high capital costs, which are strongly dependent on seabed depth, currently limit the geographical expansion of this technology to areas with relatively shallow waters and appropriate wind resource. This, along with the advantages of sharing a submarine transmission system among several projects, leads to a high concentration of offshore wind farms in certain zones, as happens, for example, in the North Sea. The presence of other neighbouring offshore wind farms has to be taken into account when a developer plans a new project, since the wake effect of wind turbines belonging to other neighbouring wind farms will affect the annual energy production and, consequently, the profitability of the project under study. However, not only already operating or installed neighbouring projects have to be borne in mind, but also the possible design of future neighbouring wind farms yet to be developed. In order to tackle this issue, an innovative co-evolutionary algorithm is proposed in this paper with the objective of determining a Nash equilibrium solution that would provide the best possible configuration of the wind farm under study by taking into account and limiting the disturbance introduced by other neighbouring projects. The performance of the proposed methodology has been successfully tested through the analysis of a realistic case and compared with other collaborative approaches and the classic single-project optimization methods already existing in the literature.

1. Introduction

Growing interest in renewable energy along with the maturity of wind technology has caused offshore wind energy to experience significant development in recent years. The offshore installed capacity in Europe rose from 4.95 MW in 1991 to 14.38 MW by the end of 2016 [1]. Offshore wind energy is not yet as mature as its onshore counterpart, but it has several advantages over onshore facilities: wind conditions at sea are usually better (the wind speeds are greater, due to lower friction provided by the water) and the wind is less turbulent (due to the absence of obstacles on the sea). These aspects lead to greater production and lower mechanical stress on the blades and the structural components.

The individual rated power of current wind turbines (WTs) in the market has achieved 9.5 MW (as the MHI Vestas V164-9.5 MW) and it is expected to keep growing in the coming years [2]. Nevertheless, in order to take advantage of economies of scale, offshore wind farms (OWFs) are usually comprised of a relatively large number of wind turbines to achieve a total rated power of several hundred megawatts (as in the case of the London Array I Wind Farm in the United Kingdom, with 175 WTs of 3.6 MW each and an overall rated power of 630 MW, which is the largest operational OWF at the time of writing this paper).

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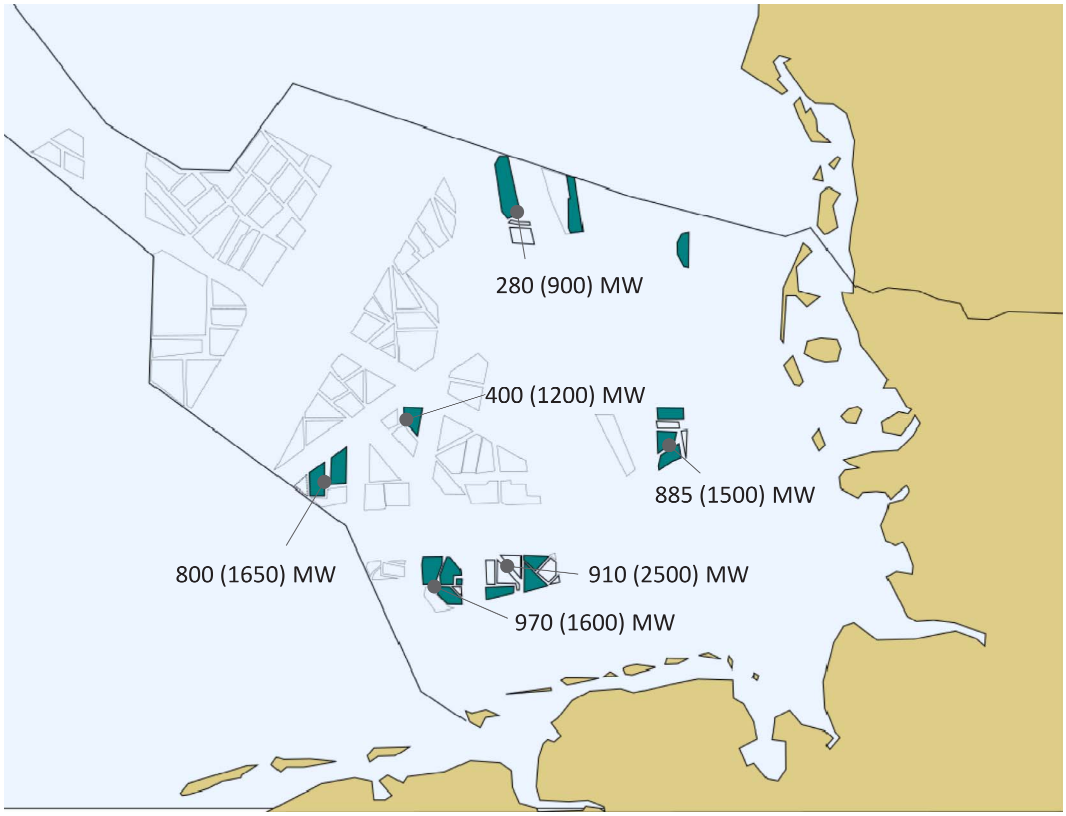

Fig. 1. Map of planned offshore wind farms in Germany's North Sea. Operating OWFs and those under construction are shaded in green. Figures concerning installed (planned, in brackets) capacity are also shown for selected areas ().
adapted from [3]

The areas where OWFs can be installed are usually defined beforehand by the relevant regulatory authority. The location of these concession areas is conditioned by various factors such as environmental conditions, distance to shore, grid connection, and seabed depth. These facts limit the offshore available space and lead the OWFs to be located relatively close to each other. This can pose a problem for the developers of new projects, since the presence of other neighbouring OWFs may reduce the energy production (because of increasing wakes), which eventually affects the economic performance of the project. Fig. 1 shows, as an example, the map of offshore wind farms in Germany's North Sea. As can be observed, most of the offshore wind projects are clustered in neighbouring areas with high installed/planned capacity. Several of the wind farm clusters are composed of projects belonging to different owners that obviously intend to individually maximize their own profits. When a developer plans the design of a new offshore wind farm in an area with a high density of projects, it has to bear in mind the possible interactions with those neighbouring wind farms. If the projects are already operating or installed, then their influence on the planned OWF can be considered by modelling the wakes produced. However, in the case where the projects nearby have yet to be planned or constructed, the developers have no means of knowing how they will affect the future profitability of their project under design. Using cooperative strategies might provide an option for the minimization of the negative impact of these neighbouring wind farms. In this case, the developers might agree to cooperate in the design of the wind farms so that the overall production is maximized. However, in many cases it is not possible to proceed with cooperative strategies either because there is no agreement among the developers or because the rest of possible OWFs in the area are still in their early phases of the project (e.g., pending planning permission or planning). In this case, the developer of a new project has to undertake the design of an OWF while considering the possible future configurations of the neighbouring turbines. Against this background, Game Theory enables a rational decision to be made so that the strategy adopted is the most appropriate for possible decisions/configurations taken by other neighbouring OWFs.

The micro-siting problem for wind turbines has been widely studied in the existing literature. In broad terms, there are 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. However, in all cases the studies focus on the optimization of one single project. The authors suggest [4–6] for a thorough literature review of this problem. In addition to the work presented within these three reviews, there are also several other relevant studies that are worth analysing. Genetic algorithms 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]. Gao et al. [10] presented, in 2015, a case study for an offshore wind farm, in Hong Kong, optimized by a multi-population genetic algorithm. An enhanced genetic algorithm combined with simulation optimization was proposed in 2017 by Yin et al. [11]. Particle swarm optimization (PSO) algorithms have also been widely used in the wind turbine micro-siting problem. In 2010, Wan et al. [12] proposed a PSO algorithm considering a continuous computational domain. This work was further improved in 2012 by including a local search strategy [13]. Chowdhury et al. [14] introduced a PSO algorithm that considered varying wind conditions. In 2015, Hou et al. [15] proposed a