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Investigation into the optimal wind turbine layout patterns for a Hong Kong offshore wind farm

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ABSTRACT

Optimal WT (wind turbine) layout patterns relate in detail to the specific conditions of OWF (offshore wind farm) environments and therefore each is different. This paper presents an investigation into optimal WT layout patterns for three OWF configurations (aligned, staggered, scattered) in HK (Hong Kong) waters. A hypothetical OWF (6930 m × 9072 m) are analysed based on twenty years of wind data (1992–2011). For the aligned and staggered WFs, different WT layout separations are studied. The separations varied between 5.0D and 15.0D along the PWD (prevailing wind direction) and 5.0D to 12.0D in the CWD (crosswind direction), where D is the WT rotor diameter. A range of 25 and 45 WTs are placed in the scattered WF, with their layout optimized using the Multi-Population Genetic Algorithm. WF performance is reported for the best ten layout patterns following studies of many different layouts. Results show for this hypothetical OWF, that the optimal WT separation is 14.5D in the PWD and 11.0D in the CWD for the aligned and staggered cases. Thirty WTs are recommended as the optimum number for the scattered WF. The LCOE (levelized costs of energy) were calculated in HK$ terms 1.474/kWh (aligned), 1.467/kWh (staggered), and 1.290/kWh (scattered). APG (annual energy generation) is determined to be 40.80 × 10^8 kWh (aligned), 40.42 × 10^8 kWh (staggered), and 33.98 × 10^8 kWh (scattered), representing 9.48% (aligned), 9.39% (staggered), and 7.89% (scattered) of the annual electricity consumption for HK in 2012. The approach presented can be regarded as a generic method for WT layout optimization.

1. Introduction

The conversion of wind energy into electricity can be realized by grouping WTs (wind turbines) to form a WF (wind farm). Large WTs are being erected around the world, both onshore and offshore [1,2], as a cleaner way of generating electricity. The relatively low turbulence characteristics of OWFs (offshore wind farms) generally allow more effective harvesting of the available energy and reduces the fatigue loads on the turbines [3]. However, turbine wake effects persist downstream of any WT [4]. From both the engineering and economic perspectives, the determination of WT layout patterns and the distances between them are key aspects of WF design [5]. Based on different wake models [6–8], several studies have proposed various WT layout optimization methods [9–13]. In these studies, the optimal locations of WTs within WFs were determined, by using objective functions which considering the maximum power generation and minimum LCOE (levelized cost of energy). The WTs were placed stochastically rather than in structured layouts. However, if landscapes are to retain an aesthetic appeal, wind farms with randomly distributed WTs are counterproductive in this respect. Additionally, if the WTs are arranged in a regular array, the cost of cabling may be less. Fewer cables not only mean reduced costs, but also reduced energy losses in energy transportation. In general the WT arrays in a WF are arranged in rectilinear grids and, depending on the local PWD (prevailing wind direction), may be perfectly aligned, staggered or scattered [14].

Many attempts have been made to optimize wind turbine positioning [10]. Array losses decrease by calculating the most efficient spacings along downwind and crosswind direction. Bansal et al. [15] stated that the land requirement of a WF, including infrastructure, is 10 ha/MW. Turbines in current offshore WFs are typically arranged in rows perpendicular to the prevailing wind direction. The distance between turbines in a row is usually of the order of 5–10 rotor diameters (5D–10D). 7–12 rotor diameters (7D–12D) is typically the distance between rows [1,16,17]. Ammara et al. [18] concluded that such layouts resulted in WT distributions which were too sparse, thus creating WFs that made inefficient use of the wind energy potential of the site.

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Nomenclatures

List of abbreviations

APG	annual power generation
CWD	crosswind direction
D	rotor diameter of the wind turbine
FCR	fixed charge rate
LCOE	levelized cost of energy
O&M	operation and maintenance cost
OWF	offshore wind farm
PC	power consumption
PG	power generation
PWD	prevailing wind direction
WF	wind farm
WFE	wind farm efficiency
WT	wind turbine

List of symbols

C_T	turbine thrust coefficient, –
r_d	wind turbine rotor diameter, m
Z_0	roughness length of ground, m
a	axial induction factor, –
u_0	free stream wind speed, m
θ	wind direction, –
P	wind turbine power generation at wind speed v, kW

List of subscripts

i	i-th wind turbine
j	j-th wind turbine

The aligned WT configuration is the most common pattern in WFs. Existing large WFs have adopted square, as opposed to parallelogram, arrangements, balancing energy output and cabling costs [19]. However, Chamorro et al. [20] performed a simplified analysis and suggested that staggered configurations were more efficient than aligned WT arrays for similar turbine separations in the downwind direction and crosswind directions. Results showed that 10% extra power output can be captured from the staggered WF. Some previous optimization studies had recommended that WTs should not be installed in grids, but instead scattered throughout the farm [9–11,13,21–23]. It has been suggested that the characteristics of a specific wind resource location may be best matched by a unique, asymmetric, site-specific WF layout [24]. Some WT layout optimization methods, based the GA (Genetic Algorithm) [9,10,21], Monte Carlo Simulation [11], and BPSO (Binary Particle Swarm Optimization) [13] have also been studied.

Extracting maximum energy from the wind within a given WF, nevertheless does depend, to a great extent, on the WT layout pattern. Optimal spacing can reduce loss of power due to wake effects. Sufficient separation must be provided to minimize wake and turbulence effects and ensure that all turbines operate at maximum efficiency. In a WF, different factors, such as the topography of the terrain, the speed and the direction of the wind, and size of the turbines, all combine to determine the optimal WT layout and their separations.

Hong Kong is located in eastern Asia, on the southeast coast of China, facing the South China Sea. This particular location provides Hong Kong with an abundance of wind. Taking Waglan Island, to the SE (south eastern) of the main Hong Kong Island as an example, the average annual wind speed during 1992–2011 was 7.07 m/s 26.3 m above ground level and 83 m above sea level, (recorded by the Hong Kong Observatory) [25]. Such an abundant wind resource clearly provides opportunities for wind power generation. Furthermore, the sea accounts for 59.91% of the Hong Kong territory area (1650 km^2) [26] and since the water depth is rarely more than 30 m, it is very suitable for offshore WT installation. An obstacle-free 1180-km coastline, as well as the very large area of sea supports the feasibility of OWF development, especially in southeastern waters. Li [27] investigated the potential for offshore wind energy in Hong Kong using the 1998 Waglan Island wind data and employing WT spacing of 5D × 5D and 10D × 5D, respectively. The optimal WT layout and separations, however, for a WF for Hong Kong conditions has not yet been determined. Lu [28,29] studied the wind power potential at five typical onshore sites in Hong Kong. The annual power generation of a single WT was calculated based on the Weibull wind data distribution parameters, but no consideration was given to the capacity of a wind farm as such.

In previous studies, WTs had been placed according to prior spacing guidelines limiting turbine-to-turbine interaction. However, the appropriate WT spacings depend upon the different wind conditions and terrain types. The main purpose of this paper is to report an investigation into the optimal WT layout separations for application in a Hong Kong OWF for the aligned, staggered and scattered layout configurations. A hypothetical OWF was posited for southeastern waters near Waglan Island. As the anticipated lifetime of a WF is typically 20 years [18–20], the last 20 years of wind data for Waglan Island was taken as the wind resource. By varying the WT layout separations along the PWD (prevailing wind direction) and CWD (crosswind directions), that configuration giving the minimum LCOE, maximum APG (annual power generation) per WT, and highest WFE (wind farm efficiency) is selected as the optimal. In the case of a scattered WF, the optimum number of WTs to be installed is included within the optimization procedure.

An assessment of Hong Kong's offshore wind power potential was also made based on the optimal WT configuration.

2. Materials and methodology

2.1. Wind farm description

Fig. 1 is a map of the Hong Kong territory with the areas unsuited to OWF development indicated by red hatching. The blank space, with a total area of 339.4 km^2 is the region potentially appropriate for OWFs [30].

The hypothetical OWF covers a sea area of 62.87 km^2 (9.072 km × 6.930 km) in the southeastern corner. The water depth is 27 m–30 m, suitable for WT installation. For this hypothetical WF, the performances of the three WT configurations, aligned, staggered, and scattered, were examined for varying WT separations.

The type of WT also influences the energy capture performance of a WF. A WT converts the wind kinetic energy to shaft mechanical energy and finally into electrical energy in a generator [31]. The available power generated by a WT is given by Eq. (1):

$$P = \begin{cases} 0; \quad V < V_{ci} \\ \frac{1}{2}\rho A V^3; \quad V_{ci} \le V \le V_{rated} \\ P_{rated}; \quad V_{rated} \le V < V_{co} \\ 0; \quad V \ge V_{co} \end{cases} \tag{1}$$

where ρ is the density of air and A is the WT swept rotor area. V_{ci} is the wind speed at which the WT cuts in and V_{co} is the cut off wind