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Optimization of Offshore Wind Farms Configuration Minimizing the Wake Effect

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Introduction

Currently, there has been a great development of the wind energy market, which is accompanied by an increase in the number of wind farms at sea, the offshore wind farms (OWF). Therefore, it is crucial to ensure that efficiency in energy production is maximum and that the levelized cost of energy (LCOE) is minimal.

A mixed-integer linear programming model (MILP) is proposed to find the best wind farm layout taking into account the wake effect in order to maximize energy production. The design of an OWF located at the North Sea is considered as a case study, contemplating three situations regarding the number of wind turbines to be installed and to determine the best positioning of them in order to maximize energy production, taking into account the wake effect and the lowest LCOE.

Optimization model

This section presents a Mixed Integer Linear Programming model to determine the optimal location of WTs in an offshore wind farm. The objective is to optimise the locations of WTs to maximise energy production, taking into account the wake effect for a given set of possible turbine locations, N, and a limit on the number of turbines to be installed. If a turbine is installed at site i, the total interference, w_i, caused by all the other turbines is given by the sum of the interference caused by each one, i.e.,

$$w_i = \begin{cases} \sum_{j \in N} I_{ij} x_j & , x_i = 1 \\ 0 & , x_i = 0 \end{cases} \quad (3)$$

Where x_i is a binary variable taking value 1 if a turbine is installed at site i. The total interference, w_i, corresponds to the reduction in energy production by the wake effect at site i. Therefore, if a turbine is installed at site i the energy produced is given by E_i - $E_i w_i$.

The objective function in the optimization model is given by:

$$maximize \sum_{i \in N} (E_i x_i - w_i E_i) \quad (4)$$

Jensen model for the wake effect

A moving air mass has kinetic energy, which depends on the air mass and the wind speed. Part of the kinetic energy is converted into mechanical energy by WTs when the air passes through the blades. The wake effect reflects the interference that the wind passing through one turbine exerts on another, reducing the air mass flow and wind speed, reducing wind energy production.

The Jensen model, illustrated in Figure 1, is used to model the wake effect in wind farms.

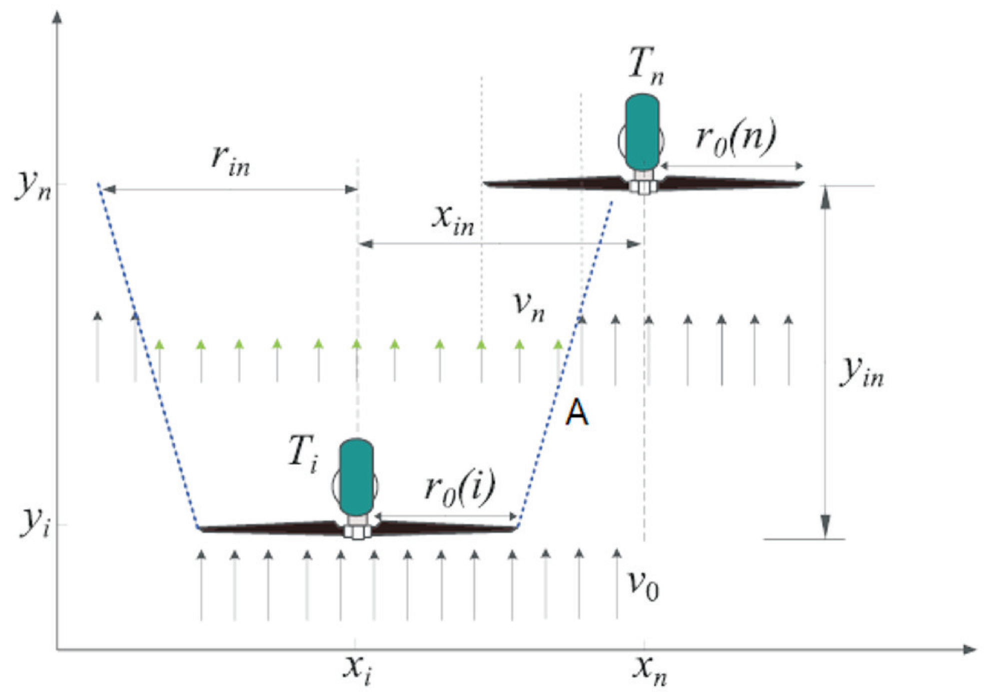

Fig.1 Principle of the Jensen wake effect model (top view) [17]

Figure *1* represents a single wake effect where T_i is located at coordinates (x_i, y_i) and T_n at coordinates (x_n, y_n), representing the upstream and downstream turbines, respectively. The wake effect is axisymmetric. It depends on the distance between T_i and T_n with respect to the wind direction, as shown in the dashed line A with the wake radius, r_{in}. The wind speed at T_n is given in Equation (5).

$$v_n = v_0 \left[1 - \sqrt{\sum_{i=0}^{N} \left[\frac{1 - \sqrt{1 - C_t}}{T} \right]^2} \right] \quad (1)$$

Where:

$$T = \left[1 + \frac{y_{in}}{2 \ln\left(\frac{z}{z_0} \right) (\alpha . y_{in} + r_0(i))} \right]^2 \quad (2)$$

Where C_t is thrust coefficient, $r_0(i)$ is the radius of the upstream turbine, y_{in} is the distance between the turbines, measured in the wind direction, and α is a dimensionless parameter and determines how fast the wake expands.

Results

Figures 2, 3 and 4 show the optimal solutions for the distribution of turbines considering at most 8, 10 and 12 turbines, respectively, contemplating the wake effect.

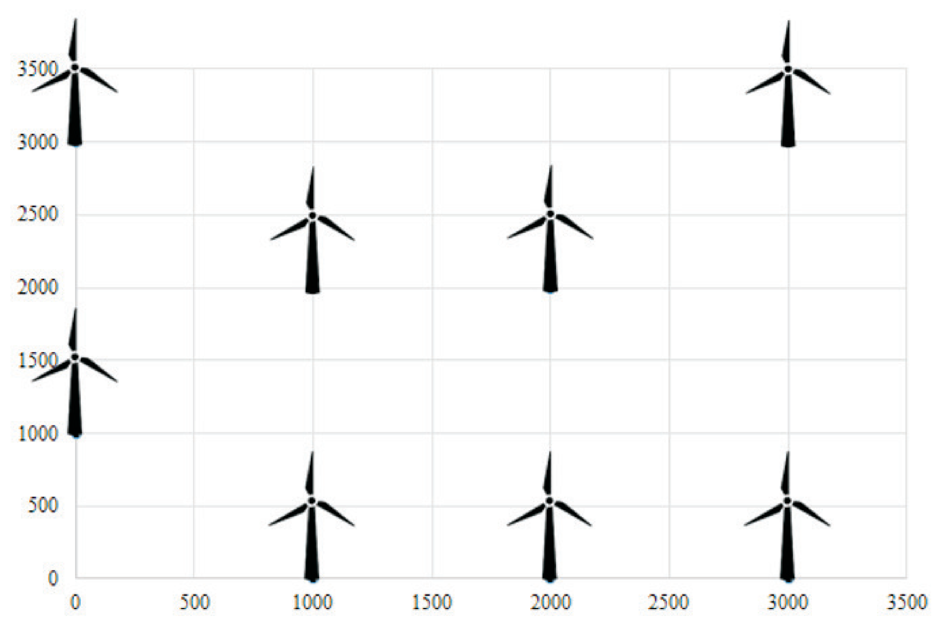

Fig.2 Optimal location of WTs when U=8

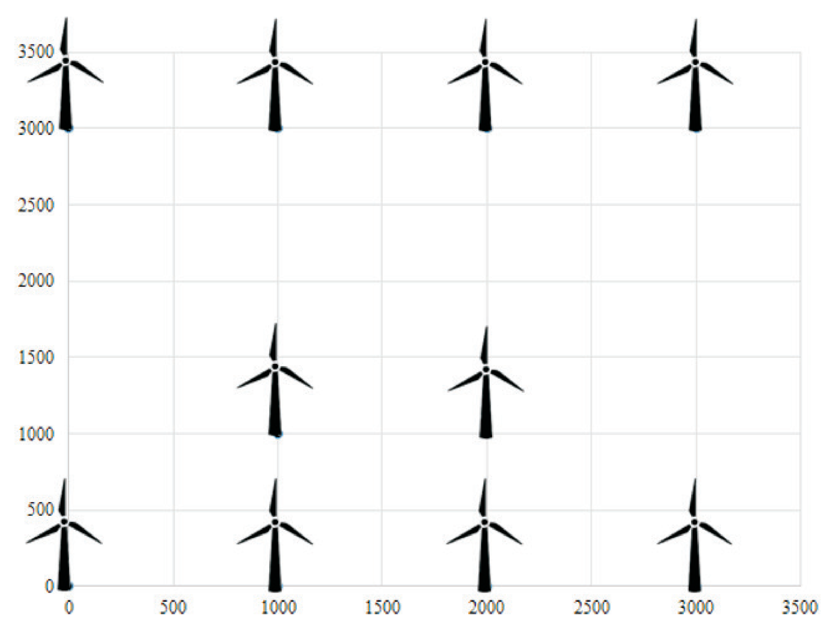

Fig.3 Optimal location of WTs when U=10

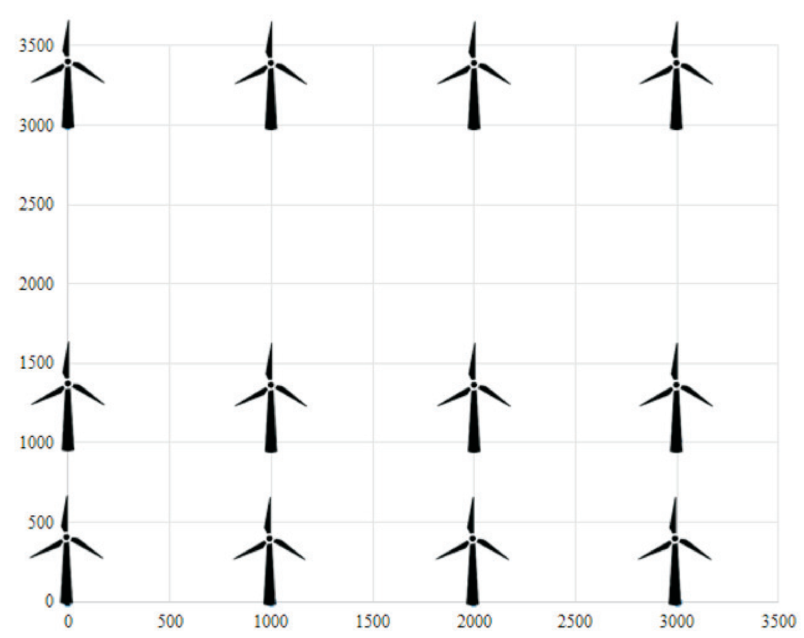

Fig.4 Optimal location of WTs when U=12

Table I Comparing results

	8 turbines		10 turbines		12 turbines	
	with wake effect	without wake effect	with wake effect	without wake effect	with wake effect	without wake effect
Annual energy production (GWh)	6510	7450	8130	9250	9620	11100
Total installed power (MW)	64	64	80	80	96	96
Average annual production per turbine (GWh)	814	931	813	927	802	925

Conclusions

The results obtained show that the MILP-based optimization model is able to achieve, with low processing times, exact optimal solutions allowing to significantly increase the efficiency of OWF.

The offshore wind farm with 8 turbines has a lower levelized cost of energy and an average output per turbine of 814 GW, which is the best value of the three cases.