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Techno-Economic Design of Wind Farms: A Methodology and Multi-Scenario Application

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Abstract

This paper aims to present a methodology and multi-scenario application for the techno-economic assessment of the wind turbine layout in a wind farm. The considered decisional variables deal with the number of wind turbines to install, their self-distance and their distance toward the primary grid line. In addition, the wind speed profile and the site boundary environmental conditions are within the methodology. The levelized cost of energy (LCOE) and the net present value (NPV) are estimated as the key results and decisional indicators to compare multiple scenarios within two relevant locations in the Middle East (a case study of Abadan site in Iran) and the Mediterranean region (a case study of Swatar site in Malta). Finally, for each site, an effective layout of the wind farm is selected. Numerical results lead to the optimum layout with the lowest cost of energy. Swatar site has the highest potential of wind for the energy production. The LCOE for this site is estimated to be 4.01 c€/kWh for a wind farm with a size of 10 MW and 5.76 c€/kWh for a wind farm with size of 25 MW. Overall, it is shown that the wind power fosters sustainable development in both case studies and the proposed structures and layouts increase the performances of the wind farms, considerably.

Keywords: Wind energy, wind farm, techno-economic evaluation, energy production.

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1. Introduction and background

The impending demise and environmental impact of global coal, oil and other fossil fuels cause insufficient energy production and high emissions from conventional energy sources leading to an upsurge attention toward sustainable sources of power [1]. Among the renewables, wind energy is among the most efficient, clean and prolific, dealing with wind farms of variable size and number of wind turbines [2, 3]. There has been a considerable attention toward the development of wind energy capacity on a global scale and, simultaneously, the research toward different aspects of wind has been carried out [4]. A key research stream deals with the wind farm layout optimization, which plays a crucial role in maximizing the energy production and minimizing the cost of energy [5]. This topic has been addressed by multiple studies in the recent past. A short review and classification is in Table 1 for years from 2002 up to date.

Table 1. Review of recent studies on wind farm design and optimization.

		Optimization goals					Methods							Wake effect	
Year	Author(s)	Energy production	Cost	Wake loss	Turbulence intensity	Noise generation	Metaheuristics and Evolutionary algorithms	Mathematical modelling	Computational Fluid Dynamics	Multi-criteria decision making	Mixed integer programming	Computer intelligence methods	Power control methods	Yes	No
2002	Rodríguez et al. [6]	x											x	x	
2003	Krokoszinski [7]	x	x					x		x				x	
2004	Barthelmie et al. [8]	x							x					x	
2005	Elkinton et al. [9]		x											x	
2006	Zhao et al. [10]	x	x				x								x
2007	Lackner & Elkinton [11]	x	x	x				x						x	
2008	Nandigam & Dhali [12]	x	x					x							x
2009	Herbert-Acero et al. [13]	x					x					x		x	
2010	Kusiak & Song [14]	x		x			x	x						x	
2011	Archer et al. [15]	x									x			x	
2012	Gonzalez et al. [16]	x	x				x			x				x	
2013	Zhang et al. [17]	x									x			x	
2014	Kwong et al. [18]	x				x	x							x	
2015	Chen et al. [19]	x	x				x							x	
2016	Sorkhabi et al. [20]	x				x	x							x	
2017	Patel et al. [21]		x				x							x	
2018	Santhanagopalan et al. [22]	x			x				x					x	
2019	Vali et al. [23]	x	x	x									x	x	

As evident from the table, several works focus on the energy production and cost as the objective of the wind farm optimization. Other technical factors include the wake loss, the turbulence intensity and the noise generation. Furthermore, different optimization and analytical methods are adopted to address the wind farm optimization problem, including metaheuristics and evolutionary algorithms, such as the genetic algorithms, mathematical modelling techniques, computational fluid dynamics, multi-criteria decision making and mixed integer linear programming. Finally, in most of the cases, the wake effect is considered during the design process.

The economic impact of energy production from wind power plants is a fundamental aspect of wind resource and energy potential assessment for any studied site. Such impact typically relies on case studies and input-output models by considering different constraints. In this study, the economic impact of the wind energy potential is evaluated.

This paper contributes to this research field by presenting and applying a techno-economic methodology for the wind farm design. Different configurations of the wind turbines are compared against common metrics, i.e. levelized cost of electricity (LCOE) and net present value (NPV), to conclude about their competitiveness and feasibility. The distance from the main grid line is, further, considered within the installation costs. Based on these goals, this paper continues with the methodology in the next section. Two case studies for the Middle East and the Mediterranean region are in Section 3, while Section 4 concludes the paper.

2. Methodology

As first step, to evaluate the viability of the wind resource and energy production, the distribution analysis of the wind speed at the blade level should be considered. In this and several literature studies, the adopted statistical distribution is the Weibull function, as in (1) [24 - 26]:

$$f(u) = \frac{k}{c} \cdot \left(\frac{u}{c}\right)^{k-1} \cdot e^{-\left(\frac{u}{c}\right)^k} \qquad F(u) = 1 - e^{-\left(\frac{u}{c}\right)^k} \tag{1}$$

where u, k and c are the wind speed [m/s], the shape factor [dimensionless] and the scale factor [m/s], respectively.

By using Eq. (1), the frequencies for the wind speed values in the studied site can be estimated, making possible to determine the probability of specific wind speed values.

Eq. (1) is used to get the wind power captured by the wind turbines in the wind farm [26]:

$$P = \eta \frac{1}{2} \rho A u^3 c_p \tag{2}$$

where P is the generated electrical power, η is the wind turbine's efficiency, ρ is the air density, A is the swept area of the wind turbine, u is the free stream wind velocity, c_p is the coefficient of power for a wind turbine. c_p follows from Eq. (3):

$$c_p = \frac{P_0}{\frac{1}{2}\rho A u_0^3} \tag{3}$$

where P_0 is the aerodynamic rated power output of the wind turbine at the nominal wind speed u_0 [27, 28].
In the case the turbine hub height, z, is different from the height of the wind data measuring system, z^*, the following equation can be used to refer the measured wind speed to the wind at the hub height.

$$u = u^* \left(\frac{z}{z^*}\right)^{\alpha} \tag{4}$$

where u is the wind speed at the hub height, u^* is the wind speed at the measuring system height and α is the so called power law exponent.

The next step in the wind farm layout design process is to determine the wind speed including the wake effect among blades of different wind turbines. In this study, the Jensen's model is considered [8]. This model is developed according to a mass-conserving engineering model to get the hub height wind speed hitting the down-wind turbine,

u_2, subjected to a hub height inflow wind speed, u_1[29]:

$$u_2 = u_1\left(1 - \left(1 - \sqrt{1 - c_t}\right)\left(\frac{r}{r+2\psi x}\right)^2\right) \tag{5}$$

where r is the up-wind rotor radius, ψ is the wake decay constant, x is the distance from the considered wind turbines and c_t is the thrust coefficient. The thrust coefficient acts as a function of an axial induction factor indicating how much the energy extracted from the turbine affects the fluid flow. The thrust coefficient can be calculated according to Eq. (6) [43]:

$$c_t = \frac{T}{\frac{1}{2}\rho A u_0^2} \tag{6}$$

where, in addition to previous notations, T is the thrust force.
Using Eqs. (1)-(6), the cumulative energy production follows in Eq. (7):

$$U = \int_{u_{min}}^{u_{max}} P(u) \cdot f(u) du \tag{7}$$

where u_{min} is the cut-in speed and u_{max} is the cut-out speed of the wind turbine [29].

The long-term sustainability of a wind farm is the economic goal of this study, while the LCOE is the indicator adopted to evaluating the overall viability of such energy projects. The LCOE, defined in Eq. (8), determines how much investments should be taken into account per unit of produced electricity to recover the system lifetime costs [26, 30, 31, 32]:

$$LCOE = \sum_{i=0}^{n} \frac{C_i \cdot (1+g)^i}{(1+r)^i} \Big/ \sum_{i=1}^{n} \frac{E_i \cdot (1+g)^i}{(1+r)^i} \tag{8}$$

where C_i indicates the annual cost of year i, n is the project lifetime, g is the inflation rate, E_i is the annual energy production of year i and r is the weighted average cost of capital (WACC) to discount the cash flows.
By including the revenues from the energy selling to the grid, the net present value (NPV) method allows calculating the economic feasibility of the energy project over its lifetime.

$$NPV = \sum_{i=0}^{n} \frac{F_i}{(1+r)^i} \tag{9}$$

where F_i is the cash flow for year i.

Starting from the proposed methodology, the next Section 3 presents applications to two relevant locations in the Middle East and the Mediterranean region.

3. Multi-scenario application to the Middle-East and the Mediterranean

A reference schematic for a wind farm connected to the grid electricity system is in Fig. 1. Multiple identical wind turbines with a 2.5MW rated power capacity are considered in this study, while different wind farm layouts by varying the positions of the wind turbines on the map are tested. Globally, multiple scenarios are developed on the basis of the number of the wind the turbines, their positions on the map and the geographical region chosen for the wind farm location. A common wind farm area of 450×450m^2 is focused. The grid and the power controller are situated next to wind farm area.

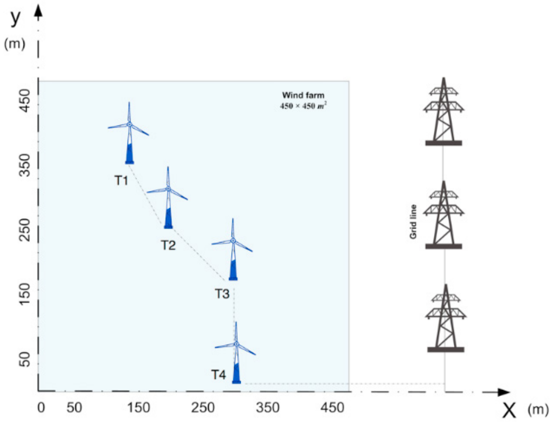


Fig. 1. Reference schematic of the proposed wind farm and the grid line.

3.1. Wind data

The multi-location analysis considers two geographical regions in the Middle East, i.e. Abadan, Iran (latitude 30.34°N, longitude 48.30°E), and the Mediterranean, i.e. Swatar, Malta (latitude 35.92°N, longitude 14.41°E). The data is extracted from two sites.

3.1.1. Geographical region #1: Abadan site in Iran – Middle East

To get wind data in Abadan site in Iran, a meteorological site is considered providing data with 10-min resolution. Wind speed values at 10m and 40m heights are extracted. Particularly, the average annual wind speed at 40m height is estimated to be 5.813m/s. According to the surface roughness and the power law equation, the surface roughness and the power law coefficient are estimated to be 0.71m and 0.268 respectively. The wind direction at 100m height is, then, estimated and depicted in Fig. 2. The prevailing wind direction is from East and a fewer proportion is from North-West.

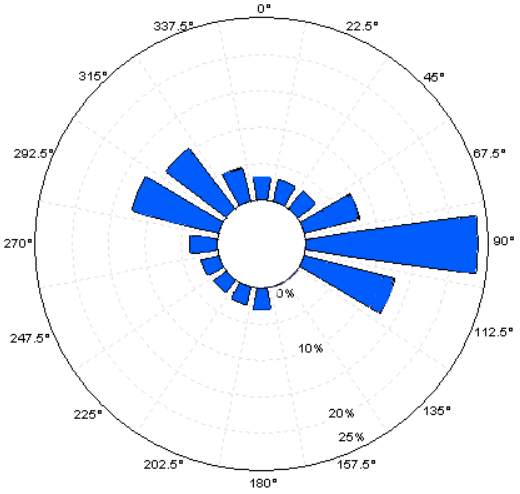


Fig. 2. The wind direction diagram at 100m height in Abadan site, Iran – Middle East.

The Weibull coefficients best fitting the wind data series are estimated to be $k = 1.77$ and $c = 5.99$m/s.

3.1.2 Geographical region #2: Swatar site in Malta – Mediterranean

The wind data for Swatar site in Malta is extracted according to previous research conducted in [33, 34]. The wind direction is estimated using a wind rose which shows that the predominant wind direction is from South-West. The average annual wind speed at height of 25m and the mean power law exponent, are estimated to 5.680m/s and 0.365, respectively. The wind direction at 100m height is, then, estimated and depicted in Fig. 3.

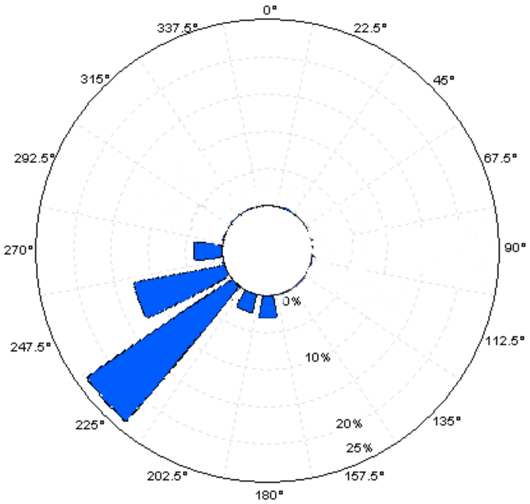


Fig. 3. The wind direction diagram at 100m height in Swatar site, Malta – Mediterranean.

The Weibull coefficients best fitting the wind data series are estimated to be $k = 2$ and $c = 6.501$m/s.

3.2. Wind turbines

In this study, 2.5MW Nordex N100 [35] wind turbines are used. Their technical and economic data are in Table 2, while Fig. 4 presents their power curve.

Table 2. 2.5MW Nordex N100 wind turbine key technical and economic data.

Parameter	Value
Hub-height	100m
Rotor diameter	100m
Swept area	7,854m^2
Loss factor	4%
Investment costs	€ 2,030,821
Annual O&M cost	€ 95,000
Annual replacement cost	€ 2,250
Lifetime	20 years

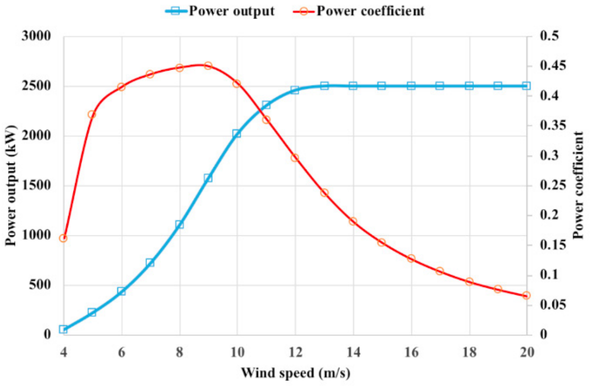
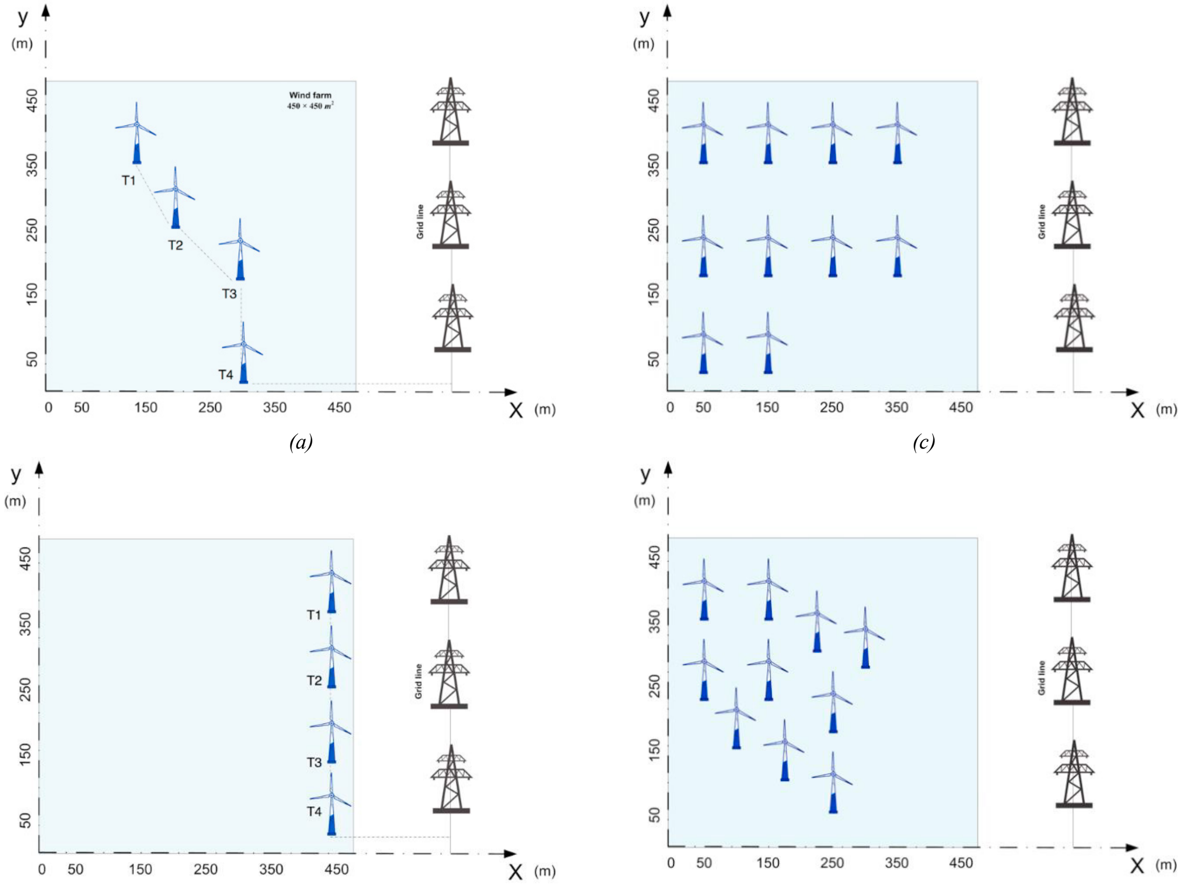


Fig. 4. The power curve of the Nordex N100 wind turbine.

Furthermore, no yaw control is applied during the analysis and it is assumed that the blades are orthogonal to the wind direction.

3.3. Tested layouts

For both geographical regions two scenarios are studied, i.e. 4 wind turbines (10MW wind farm) and 10 wind turbines (25MW wind farm). Such scenarios model mid and high size wind energy sites. In addition, for each scenario, two feasible layouts are compared. These layouts are designed on the basis of arrangement of the wind turbines in the wind farm and their distance between the turbines and the primary grid line.



(a) (c)

(b) (d)

Fig. 5. Tested layouts for 10MW *(a)-(b)* and 25MW *(c)-(d)* scenarios.

3.4. Results and comparison

For each scenario and layout, the overall annual energy production is estimated applying Eq. (7). Results are in Table 3 for the scenarios and layouts of Fig. 5.

Table 3. Annual energy production for the considered scenarios and layouts [MWh/year].

	10MW scenario		25MW scenario	
	Layout (a)	*Layout (b)*	*Layout (c)*	*Layout (d)*
Abadan (Iran)	33,549	36,356	43,973	72,796
Swatar (Malta)	44,501	44,304	83,900	83,790

Starting from such values, the economic dimension is introduced computing the initial investment and annual costs for the two scenarios. For the shake of simplicity, in both cases, the WACC is equal to 8% and the inflation rate is of about 10%. Such data allows computing, for each geographical region, scenario and considered layout, the expected LCOE and NPV over the 20 years' lifetime. Aggregated results are in Table 4.

Table 4. Economic performances for the considered scenarios and layouts.

		10MW scenario		25MW scenario	
		Layout (a)	*Layout (b)*	*Layout (c)*	*Layout (d)*
Abadan (Iran)	*LCOE*	5.080 *c€/kWh*	4.88 *c€/kWh*	12.321 *c€/kWh*	6.642 *c€/kWh*
	NPV	€ 10,789,185	€ 11,700,357	€ 2,188,157	€ 8,117,478
Swatar (Malta)	*LCOE*	4.01 *c€/kWh*	4.012*c€/kWh*	5.763 *c€/kWh*	5.771 *c€/kWh*
	NPV	€ 15,278,748	€ 15,212,666	€ 10,079,727	€ 10,060,375

The economic analysis of the wind energy production in two studied sites indicates that the LCOE varies from a minimum of ~4c€/kWh in Swatar for layouts *(a)* and *(b)* up to maximum of ~12c€/kWh for layout *(c)* in Abadan. The overall comparison of the economic parameters for the two studied sites shows that Swatar has a higher NPV and lower LCOE values making it a more suitable site. It is also noted that in both two studied sites, the 10 MW scenario is more viable and effective. Using this scenario and considering the NPV values, in Swatar, the best solution is layout *(a)*, while in Abadan the most suitable solution is layout *(b)*. It is also concluded that, due to the wake effect, the presence of a predominant wind direction plays a substantial role in achieving better power performances.

4. Conclusions and next steps

In this study, a methodology for the design of a wind farm is presented and applied to two relevant geographical regions in the Middle East and the Mediterranean region. Starting from a review of the latest advancements in the field, the technical and economic parameters to predict the performances, driving the wind farm design phase, are outlined. In the design process, given the geographical site, the main degree of freedom deals with the best positioning of the wind turbines, defining the site layout and highly affecting the energy performances due to interferences between up-wind and down-wind turbines respect to the wind direction.

The outcomes of the multi-scenario application allow driving practitioners in predicting the cost of energy and overall convenience in investing in the wind source. In the proposed multi-scenario application, the Swatar site, in Malta – Mediterranean region, has shown good potential for wind power production for both mid and high size farms. Extensions to other regions, different wind turbine models, even mixed together, and the proposal of feasible optimal models to locate the wind turbines, given the site morphology, are among the possible future developments.

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