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Wind turbines farms applications. A mini review

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Abstract
In the modern era, the coverage of energy needs is constantly shifting towards Renewable Energy Sources for both environmental and economic reasons. Wind, being an inexhaustible energy source freely available in nature, requires no human intervention for its utilization. The harnessing of wind energy and its conversion into electricity involve capturing the kinetic energy of the wind through wind turbines, which then transfers the generated power to electrical grids. Wind energy capture is achieved through the use of wind turbines placed in wind parks. In recent years, the number of wind parks has increased, driven by the petroleum crisis. Initially, the cost was prohibitively high, limiting their usage. However, ongoing technological advancements have made the use of wind turbines more frequent and necessary, as there is an observed increase in the amount of energy produced. Through simulation, we are afforded the opportunity to observe and test behaviors without the need for real-world application. In this study, we will present simulations of wind turbine parks and their applications.).
Keywords*:* Wind energy, Renewable energy sources, Wind farms.

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I. INTRODUCTION

Many studies have been conducted on the investigation of wind turbines, as their use is related to the generation of electrical energy through wind power, which is a renewable energy source. But what is wind energy? It is a form of energy produced by the movement of atmospheric air and is influenced by factors such as the Earth's rotation around its axis, the terrain's topography, and solar radiation. Wind energy is one of the developing energy sources globally, competing with solar energy. Many wind turbines placed in a specific area - wind farms - with high wind potential lead to an increased concentration of energy. Wind farms are categorized into two types: (1) offshore and (2) onshore.

However, they present certain disadvantages (high cost, difficulty in storage, site suitability, noise, etc.) as well as advantages (inexhaustible energy source, self-sufficiency, positive environmental footprint, etc.). There are limited data from the wind turbines application in urban environments because their use is not common in these settings. After numerical and experimental research, both in the field and in aerodynamics laboratories ([2], [3], [4], [5], [6]), we observe that, at least for now, the power output of wind turbines in urban environments is low [7].

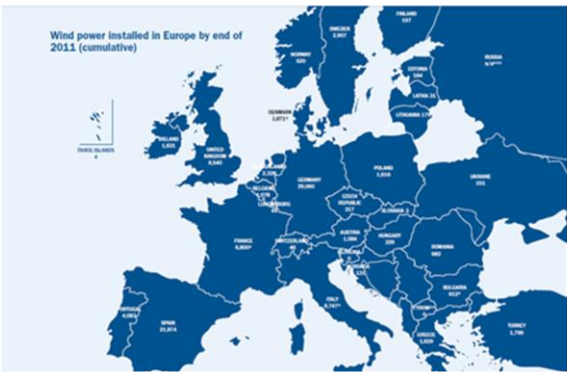

Figure 1: Total installed wind energy in Europe until the end of 2011 (adapted from [1])

Chong et al. [8] designed an Omniflow-Direct-Driven-Vane (ODGV) integrated with a Vertical Axis Wind Turbine (VAWT) for urban applications. Aiming to reduce carbon emissions, the British government has implemented programs for the development of microgeneration technologies, specifically the Low Carbon Buildings Programme, the Code for Sustainable Homes, and the Feed-in Tariffs Order ([9], [10]). Such microgeneration technologies also include small wind turbines [11, 12]. In urban areas, rooftop wind turbines have recently garnered interest due to their low transmission costs and the high potential for energy efficiency resulting from wind acceleration between buildings. The height of a building influences the wind pattern, with a potential increase in energy yield. However, the application of wind turbines in urban areas faces challenges due to atmospheric turbulence. The placement of wind turbines needs to be carefully examined for each location, considering airflow conditions and turbine performance.

A relatively new wind turbine technology leverages high altitudes and wind dynamics to generate significant electrical energy. These turbines, known as High-Altitude Wind Energy, primarily exploit the high wind speeds, making them efficient in producing energy compared to other wind power methods.

There have been various studies conducted for the establishment of wind farms in different regions of the world. These studies cover several aspects, like wind potential, geological studies, environmental assessments, economic studies and technological analyses. Various studies have taken place to find the most suitable location for the construction of a wind farm. It is important to consider the wind potential of the area, which depends on its topography, such as the tunnel effect (where the terrain resembles a tunnel). Additionally, the impact on wind speed was studied when placing wind turbines between mountains [13]. Furthermore, according to research, the placement on a hill slope affects pressure vectors [14].

Finally, in uneven terrain, significant disturbances in the wind have been observed, with particularly high wind pressures and flow separation [15].

The simulation of a wind farm by Papazisis et al. [16] utilized Computational Fluid Dynamics (CFD) in a computational domain using the ANSYS CFX fluid dynamics analysis program. The simulation focused on modeling the tower of the wind turbine without the rotor, and three tests were conducted where the distance between the towers varied. Latinopoulos and Kechagia [17] proposed and applied a comprehensive assessment framework for selecting areas suitable for wind farm development. Geographic Information Systems (GIS) and spatial decision analysis of 41 multiple criteria were utilized for this purpose.

In Greece, studies were implemented for both onshore and coastal wind parks in island areas due to increased wind potential ([18], [19]). Al-Shabeeb et al. [20] conducted a study to find suitable locations for wind turbines in Jordan using the Analytic Hierarchy Process (AHP). Rezaian and Jozi [21] sought the appropriate location for a wind farm in Takestan Plain, using the Analytical Hierarchy Process (AHP) for multi-criteria decision-making. Van Haaren and Fthenakis [22] presented a new method for selecting wind park locations in New York, considering cost-effectiveness optimization. Kim et al. [23] focused on creating offshore wind parks around the Korean Peninsula. Yun-na et al. [24] conducted a study to find suitable locations for a wind/solar hybrid power station in China based on the Ideal Matter-Element Model. Kang et al. [25] used fuzzy AHP to rank the performance of existing wind parks in Taiwan. Sareni et al. [26] used a multi-objective genetic algorithm to examine the results of a low-cost structure wind generator. The present review gives a brief overview of simulation models of wind turbine systems and wind turbine placement effects.

II. BRIEF OVERVIEW OF THE MATHEMATICAL MODEL

In this work indicative examples presented below are conducted using a 3-Dimensional Computational Fluid Dynamics (CFD) model [27, 28, 29]. The mathematical model of the turbulent flow used in the wind turbine simulations consists of the Reynolds-Averaged Navier-Stokes (RANS) equations coupled with the k-ε turbulence model. Each primitive flow variable is decomposed to an averaged-in-time part and a fluctuation term. For example, the velocity vector at a point in the flow field is given as the sum of the time-averaged velocity $\bar{\vec{U}}$ and a time-dependent velocity fluctuation $\vec{u}$, i.e., we write

$$\vec{U} = \bar{\vec{U}} + \vec{u} \quad (1)$$

The time-averaged velocity vector is defined as

$$\bar{\vec{U}} = \frac{1}{\Delta t}\int_{f}^{f+\Delta t} \vec{U} dt \quad (2)$$

where T is a time interval much longer than the characteristic periods of the turbulence fluctuations. The use of mean values (in time) in the conservation equations leads to the Reynolds-Averaged Navier-Stokes (RANS) equations:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{U}\right) = 0 \quad (3)$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \bullet \left(\rho \vec{U} \otimes \vec{U} \right) = \nabla \bullet \left(\tau - \rho \overline{\vec{u} \otimes \vec{u}} \right) + \vec{S}_M \quad (4)$$

In Equation (4), $\rho \overline{\vec{u} \otimes \vec{u}}$ are the Reynolds stresses and τ denotes the stress tensor due to molecular viscosity. After introducing the concept of an effective viscosity, μ_{eff}, the conservation of mass equation is unchanged and the conservation of momentum equation is written as

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \bullet \left(\rho \vec{U} \otimes \vec{U} \right) - \nabla \bullet \left(\mu_{eff} \nabla \vec{U} \right) = -\nabla p' + \nabla \bullet \left(\mu_{eff} \nabla \vec{U} \right)^T + \vec{B} \quad (5)$$

where $\vec{B}$ is the total body force per unit mass, μ_{eff} is the effective viscosity and p′ is the modified pressure defined as

$$p' = p + \frac{2}{3} \rho k + \nabla \bullet \vec{U} \left(\frac{2}{3} \mu_{eff} - \zeta \right) \quad (6)$$

In Equation (6), ζ is the fluid bulk viscosity, ρ is the fluid density and k denotes the turbulent kinetic energy.The k-ε model is used in this work for the calculation of the turbulent viscosity at each point of the flow field. The k-ε model is a two differential equation model where the effective viscosity is calculated as the sum of turbulent viscosity (μ_t) and molecular viscosity (μ) i.e.,

$$\mu_{eff} = \mu + \mu_t \quad (7)$$

The turbulent viscosity is computed at each point of the flow field in terms of the turbulence kinetic energy, k, and the turbulence kinetic energy dissipation rate, ε, by the relation

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \quad (8)$$

where $C_\mu = 0{,}09$

The required values of k and ε are computed at each point of the turbulent flow field by concurrently solving the following two partial differential equations [18]:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \bullet (\rho \vec{U} k) = \nabla \bullet [(\mu + \frac{\mu_t}{\sigma_k}) \nabla k] + P_k - \rho \varepsilon \quad (9)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \bullet (\rho \vec{U} \varepsilon) = \nabla \bullet [(\mu + \frac{\mu_t}{\sigma_\varepsilon}) \nabla \varepsilon] + \frac{\varepsilon}{k} (C_{e1} P_k - C_{e2} \rho \varepsilon) \quad (10)$$

where $C_{e1} = 1{,}45$, $C_{e2} = 1{,}90$, $\sigma_k = 1{,}00$, $\sigma_\varepsilon = 1{,}30$ and P_k is the rate of production of turbulence kinetic energy calculated by

$$P_k = \mu_t \nabla \vec{U} \bullet (\nabla \vec{U} + \nabla \vec{U}^T) - \frac{2}{3} \nabla \bullet \vec{U} (3 \mu_t \nabla \bullet \vec{U} + \rho k) \quad (11)$$

The ANSYS-CFX [28] computer package is used in this work under the assumption of incompressible flow with constant properties (ρ= constant, μ= constant) and bulk viscosity ζ=0.

In many other examples the Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) were employed. Geographic Information System (GIS) could be utilized for renewable energy project siting. Site selection criteria can be developed to determine the optimum locations for wind farms and even positions of individual turbines to maximize resource potential [20].

III. INDICATIVE EXAMPLES

In the simulation conducted by Papazisis et al. [16], a study of three sets of wind turbines was performed using a 3-Dimensional Computational Fluid Dynamics (CFD) model. The computational domain has been discretized using tetrahedra, wedges and pyramids elements (see Fig.2). The significance of the distance between the two towers in creating a wind farm was demonstrated.

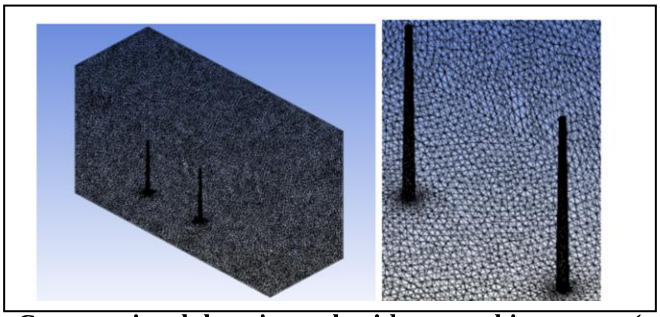

Figure 2: Computational domain mesh with two turbine towers (adapted from [16])

Therefore, the appropriate selection of distances between wind turbines is a necessary condition for designing both onshore and offshore wind parks (Fig.3). The results of this study can currently be applied to the design of offshore wind park layouts.

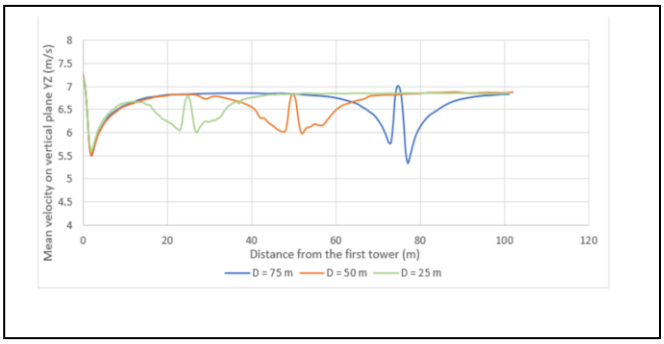

Figure 3. Average velocity per different separation distance.

In the research by Al-Shabeeb et al. (2016), Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) were employed to identify the most suitable location for establishing a wind park. The preselection of wind turbine placement in northwest Jordan was based on available natural data for the region using the Analytic Hierarchy Process (AHP) method within the GIS environment. The results of this study showed that, considering natural factors, 45% of the examined areas are the most suitable. The findings of this research can be used to contribute to the effective design of renewable energy (wind turbine) management for ensuring sustainable development of renewable energy in Jordan and other energy-deficient areas. Additionally, the research will contribute to enhancing available renewable energy resources in Jordan and the sustainable socio-economic development of the country. The final suitability map of this research is presented in Fig. 4.

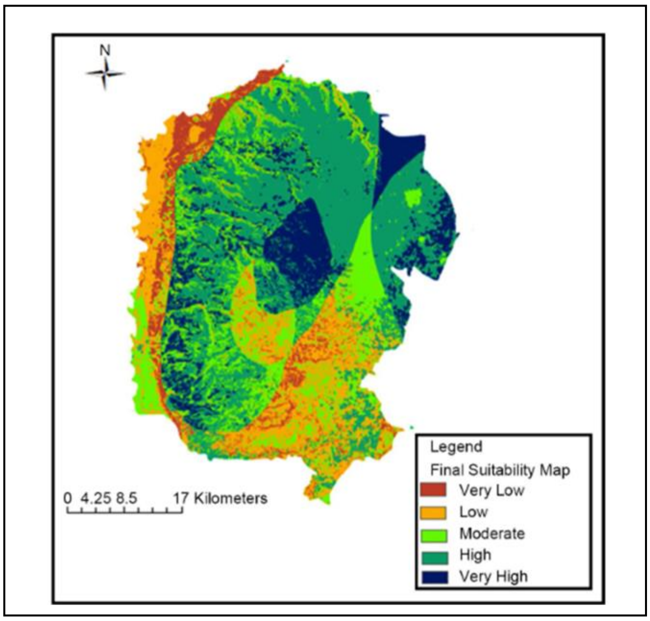

Figure 4: The final suitability map. (adapted from [20])

In the study by Sareni et al. [26], a "low-cost fully passive structure" for a wind turbine system is proposed. Such a system needs to have its design parameters adjusted positively to operate efficiently. Therefore, several sizing and simulation models of the passive wind turbine system have been developed. The Pareto-optimal configurations of the passive wind turbine system are presented in Fig. 5.

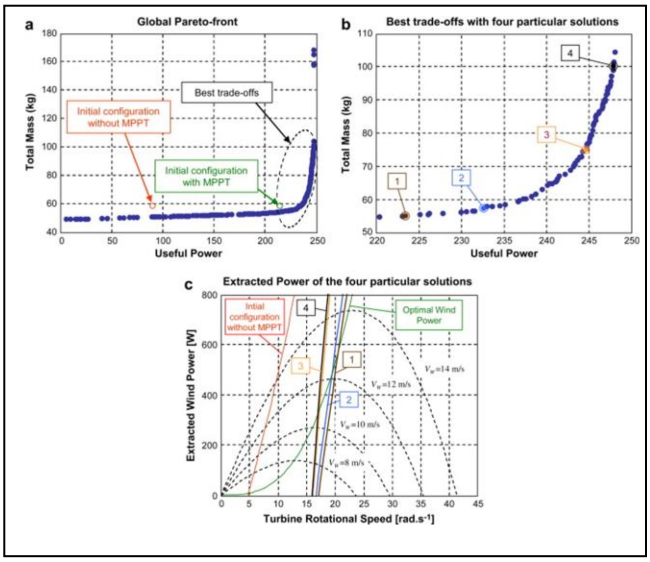

Figure 5: Pareto-optimal configurations of the passive wind turbine system. (adapted from [26])

The final result of the study from Latinopoulos and Kechagia [17] the GIS-based MCDM analysis illustrates how land suitability varies for the development of wind parks. The grid layers are defined between 0 (unacceptable location) and 1 (ideal location), displaying the overall Suitability Index (SI) score according to the decision factors (criteria) of the simulation program.

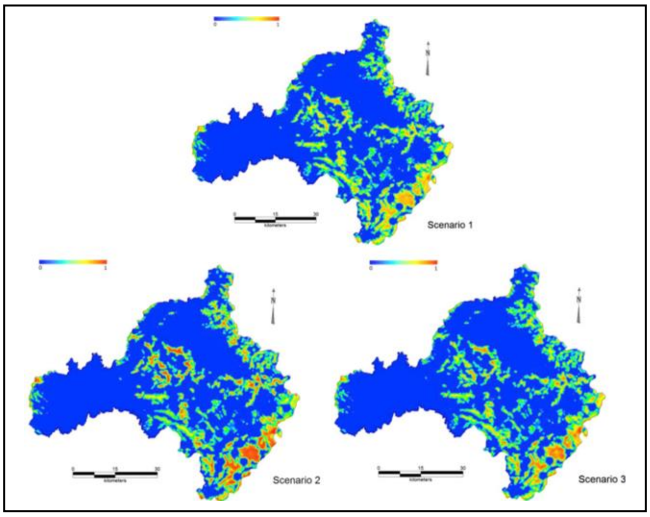

Figure 6: Land suitability maps. (adapted from [17])

IV. CONCLUSION

The use of wind energy as a renewable energy source with an environmentally friendly footprint has directed many countries towards a new energy policy based on wind power. Studies and implemented programs take into account resource availability, site selection, technological data, energy balances, economic and social impacts, and implementation strategies.

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