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Wind Resource Assessment Methods. Mathematical Optimization Methods

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ABSTRACT

This article is devoted to overcoming the contradiction between the problem of maximizing theextraction of wind energy as the goal of optimizing wind turbines, and the use of traditional methods basedon criteria for the aerodynamic quality of the blades. A modified technique is considered in which theoptimization criterion is the directly extracted flow power. It is based on pulse theory methods that use specificpower as an optimization criterion. A comparative analysis of the energy efficiency of different types ofturbines is carried out, and the effects of blade inversion are considered. A method for calculating multi-rotorturbines based on the concept of uniform power distribution is presented. The compatibility of proprietary andtraditional methods is considered by comparing the results of numerical experiments with calculated andexperimental data from sources. Optimization computational algorithms generate data from numericalexperiments and determine optimal parameter configurations for the turbines under consideration. It is shownthat orthogonal Darrieus turbines in high-speed mode provide energy efficiency comparable to collinearturbines, and multi-rotor turbines with power uniformly distributed over the working section are not inferiorin energy efficiency to basic turbines, with linear blade velocities halved.

Keywords: Collinear; Orthogonal; Modified; Power; Criterion; Optimization; Uniform Distribution; Multi-Rotor

Introduction

The foundation of the world's wind power plant fleet consists of bladed turbines that transformthe kinetic energy of the forward airflow into the operation of rotating electric generators, pumps, compressors and other power devices. More than 90% of wind power plants are equipped withturbines featuring a horizontal axis of rotation oriented parallel to the airflow (Figure 1). For thepurposes of this study, such turbines are classified as collinear. Turbines can be made with a different number of blades: from single-blade with counterweightsto multi-blade configurations numbering dozens of blades (Figure 2). The most common turbineshave three blades. The objects of this study are bladed wind turbines. Setting the optimization problem for suchturbines involves the formation of a special classification of factors that determine their functioning. Each factor is characterized by a corresponding parameter or combination of parameters. In a broadformulation, factors are divided into natural (external) factors that are not amenable to regulatoryinfluence within the boundaries of ordinary tasks, and particular (internal) regulated factors. In turn, it is advisable to divide your particular factors into basic and additional ones. Examples of natural factors are wind speed and direction, humidity and air density, environmental restrictions (taking into account regulatory regulations) and others. As for theparticular factors, their classification is determined by the structural features of the objects underconsideration. In the context of this study, structurally turbines, as objects of study, are divided into basic -collinear and orthogonal, and modified - supplemented with special structural elements or modules. The following modification options are considered as examples. Renewable energy is increasingly important for reducing pollution, reducing CO_2 emissions, mitigating climate change and promoting sustainable development [1]. The world is undergoing an energy transition to limit climate change, and accelerating the use of clean energy is a key driver of this transition [2].

Figure 1: Wind installations with collinear turbines.

The Intergovernmental Panel on Climate Change (IPCC) has highlighted the need for urgent action to limit the increase in global average temperature to 1.5 °C. Total annual greenhouse gas emissions, approximately 14.6 Gt CO_2eq, can be attributed to the burning of coal, which accounts for about 30% of total greenhouse gas emissions [3]. Figure 2 shows the average monthly carbon dioxide concentration since 2000. It can be observed that there was an increase of 5.27% between 2000 and 2010, 11.95% between 2000 and 2020 and 14.44% by January 2024. Renewable energy sources are a significant alternative to burning fossil fuels. The International Energy Agency emphasizes that the development of hydro, wind and solar energy is crucial to achieving the global goal of "net zero" greenhouse gas emissions [4]. The amount of electricity produced from these renewable sources depends largely on weather conditions. Changes in wind speed and direction affect the sustainability of energy production in wind power plants. Renewable energy production from wind is one of the most effective ways to reduce carbon emissions and achieve carbon neutrality [5]. However, as global warming will change atmospheric circulation patterns, wind resources may be affected by climate change [6].

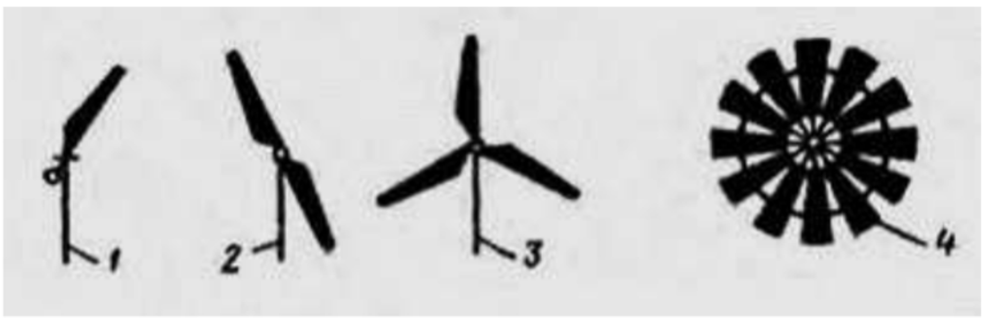

Figure 2: Schemes of collinear wind turbines: 1 - single-blade with counterweight, 2, 3, 4 - two-, three-, multi-blade.

Due to the evolution of atmospheric motion patterns under global warming and climate variability, significant changes in the spatial and temporal distribution of wind resources may occur in the future. Wind energy assessment requires the collection of data and the use of analytical methods and techniques to estimate the wind availability over the life of a wind turbine. Information about wind availability is essential for determining how much energy a wind power plant will produce, determining its operating mode, and ultimately assessing its economic viability. Therefore, it is important to use successful forecasting models to make useful predictions about the wind energy potential of interest for the long-term development of wind farms. [7] Before installing a wind turbine, wind resources should be measured and analyzed to assess the wind energy generation potential and select the appropriate wind turbine model. [8,9] The power produced by a wind turbine varies significantly depending on the wind speed distribution, even if the average wind speed is the same. This is because wind energy is defined by the cube of the wind speed, and the average wind speed is defined by the arithmetic mean. In general, wind resources should be measured for at least one year (Kose, 2004; Kang et al., 2021), but there are several limitations, including issues related to site selection, installation of weather masts or LiDAR after physical and geotechnical ocean surveys, and additional maintenance costs. [10,11] Conduct an analysis using annual measurements of wind characteristics and meteorological parameters to determine the most suitable type of wind turbine that can be installed at a given location for electricity generation.

The wind potential analysis showed that the analyzed site is suitable for the development of a wind power plant. The analysis was carried out for six different types of wind turbines with a capacity ranging from 1.5 to 3.0 MW and a shaft height of 80 m. The wind energy potential was assessed using Weibull analysis. The values of the scale factor c were determined and a large monthly variation was observed, with values ranging from 1.92 to 8.36 m/s and an annual value of 4.95 m/s. The monthly values for the shape factor k varied from 0.86 to 1.53, with an annual value of 1.07. In addition, the capacity factors of the turbines varied from 17.75 to 22.22%. The Vestas turbine with a nominal capacity of 2 MW and a capacity factor of 22.22% proved to be the most efficient wind turbine for the specific conditions in which it was located. The amount of greenhouse gas emissions that would be reduced if this type of turbine were applied was also calculated taking into account the average CO_2 emission intensity factor ($kgCO_2/kWh$) of the national electricity system. (Figure 3). Probability density function Several statistical distributions are important for the characterization and analysis of wind resource data, including the widely used Rayleigh and Weibull distributions. Among the various statistical methods available for modeling wind speed data, the Weibull distribution is an effective and reliable choice. The reason for its widespread application in the wind energy field can be attributed to its ability to accurately describe the characteristics of wind data. In this study, the wind speed potential at a selected location was estimated using the Weibull probability density function. The statistical tool can be used to characterize the probability distribution of wind speeds. The probability density function of the measured wind speed was obtained by dividing the data sets into 1 m/span intervals and calculating the percentage of data points for each interval. The mathematical form of the Weibull distribution function is given by the following expression:

$$f_{(v)} = (\frac{k}{c}) = (\frac{\gamma}{c})^{k-1} \exp\left[(\frac{\gamma}{c})^{k} \right]$$

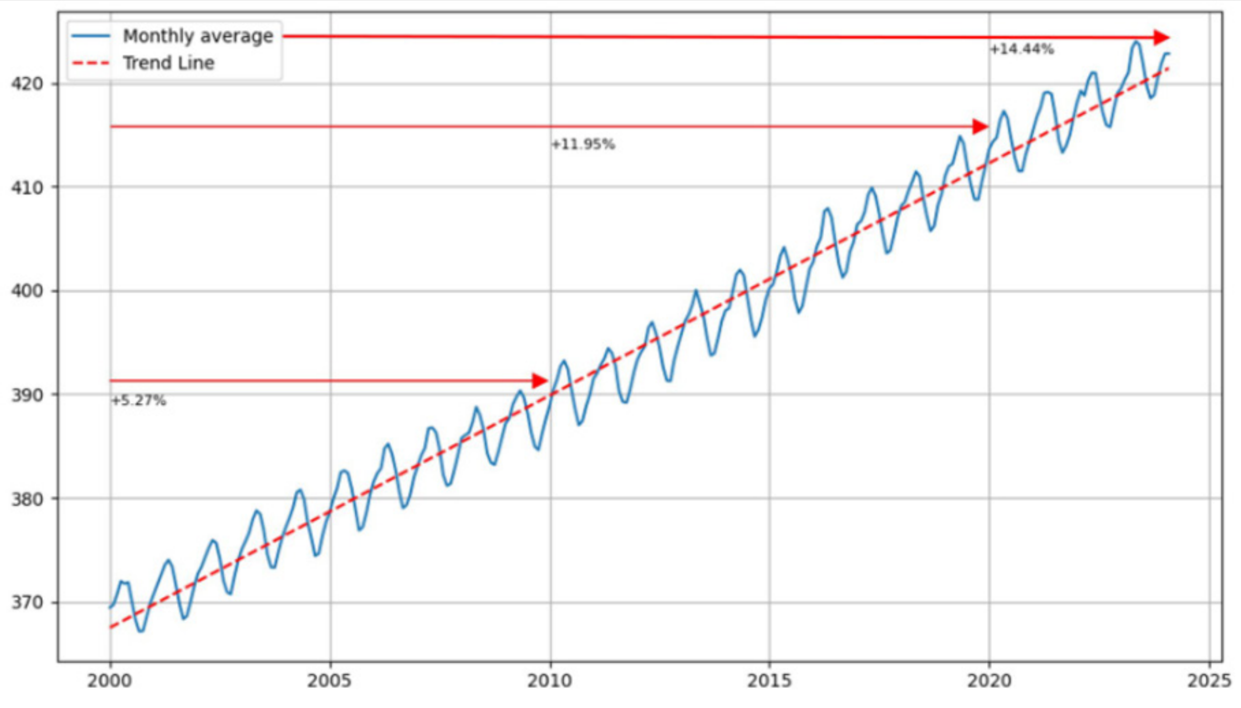

Figure 3: Global average atmospheric carbon dioxide (ppm) [12-15].

(Figure 4) In this context, the variable 'v' represents the magnitude of the wind speed, 'k' the shape parameter, and 'c' [m/s] the scale parameter associated with the Weibull distribution. The shape factor k and scale factor c are defined by the following equations, respectively:

$$K = (\frac{\delta}{v})^{-1.086}$$

$$C = \frac{v}{\Gamma(1+\frac{1}{k})}$$

In the given expression, v denotes the average wind speed, σ denotes the standard deviation of the wind speed, and Γ denotes the gamma function. The gamma function, known as the extension of the factorial function to complex numbers, is formally expressed as follows:

$$\Gamma_{(X)} = \int_0^{\infty} t^{x-1} e^{-t} dt$$

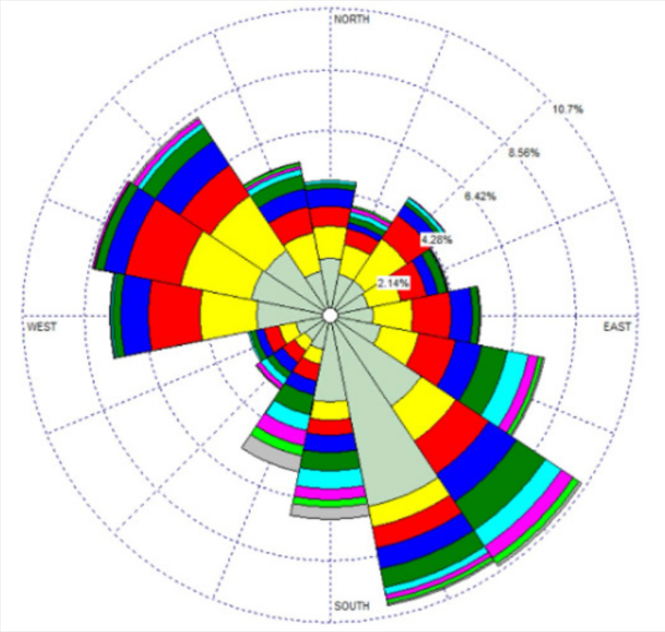

Figure 4: Wind rose at the analyzed location.

By applying this probability distribution to recorded wind speed data, researchers can gain valuable insights into the characteristics of the wind resource. This information is essential for the effective planning and implementation of wind energy systems in the study area. The use of this statistical methodology significantly improves our ability to efficiently utilize renewable energy sources, thereby contributing significantly to the implementation of sustainable energy practices. The study takes the energy storage equipment in the distribution network as the activeregulation unit and the group-switching capacitor bank as the reactive power regulationunit, respectively. The operation amount of the regulation equipment is converted intoeconomic cost, the active power is used to express the operating state of the distributionnetwork uniformly, and the minimum operating cost is taken as the objective function,so that the optimisation model of the distribution network operation under the windand photovoltaic access is established, and the particle swarm algorithm is used to findthe optimum. The example scenario is set up using IEEE node system data, wind andsolar output data, and time-sequence load data. Wind power generation, as a renew-able energy technology, utilizes the wind energy of the Earth's climate system to generateelectricity. Wind power is a widely existing resource that is not only endless and clean,but also meets society's demand for sustainable energy (Catalán et al. 2023; Tang et al.2023). Figure 1 shows the model of wind turbine power generation equipment selectedin the study. In Figure 5, wind power generates electricity by converting wind power into electricalenergy. The blades of a wind turbine rotate under the action of wind, and mechanicalenergy is transmitted to the generator through the shaft. The relative motion betweenthe rotor and stator generates electromagnetic induction, which in turn generates cur-rent. The obtained electricity is regulated by transformers and connected to the powergrid to provide electricity to users. The power generated by the wind turbine is repre-sented by Eq. (1)

$$p_{i,t}^{W} = 0.5 \rho_{\alpha} A_{l} . v_{l,t}^{3}$$

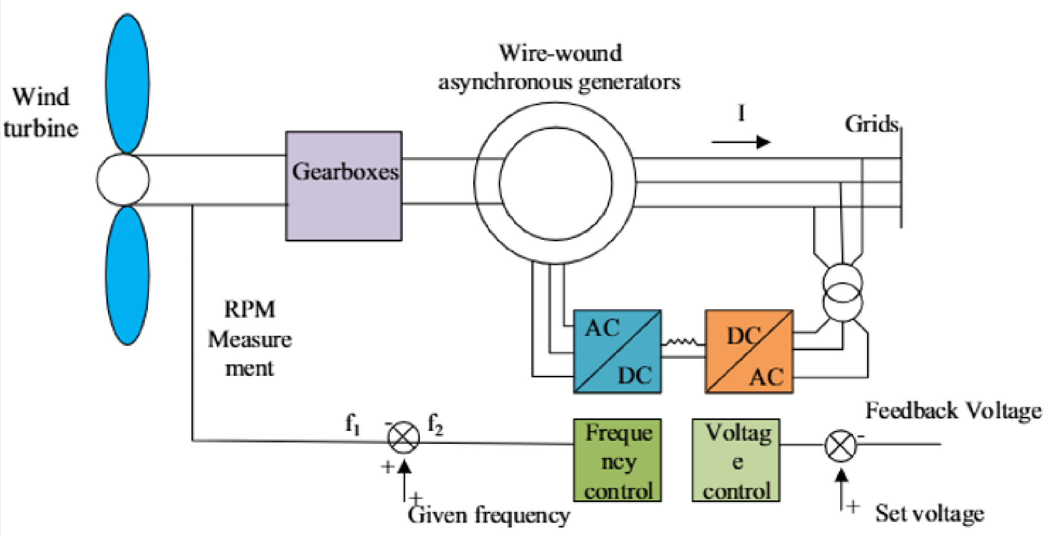

Figure 5: Model of wind turbine power generation equipmen.

İn Eq. (1), $p^{W}_{i,t}$ represents the maximum value of device power. $p^{W}_{i,t}$ represents air den -sity. A_i is the coverage area of the fan blades. v3i,t represents wind speed. The formula forthe active power supplied by a wind turbine can be obtained from the air density, thewind speed, the area swept by the fan blades. As mentioned in the Introduction, this paper describes eight different strategies used to optimize the same wind farm layout. The objective of this case study was to maximize the Annual Energy Production (AEP) of a wind farm, based on the Borssele III and IV wind farms, by optimizing the placement of 81 wind turbines. The turbines are 10 MW machines with 198 m rotor diameters based on the IEA 10 MW reference wind turbine (Bortolotti et al., 2018). The wind farm boundary for this case study was split into five discrete regions, shown in Figure 6. The presence of unconnected regions in the wind farm boundary can be challenging when an algorithm requires a continuous objective function or derivatives. The wind turbines can be placed in any of the five regions of the wind farm, but not between them, making the problem inherently discontinuous and non-differentiable. We used a simple Gaussian wake model based on Bastankhah's Gaussian wake model (Bastankhah and PortéAgel, 2016), and presented in the IEA case study 3 and 4 announcement documents (Baker et al., 2021), to calculate wind speeds at each turbine in the wind farm.

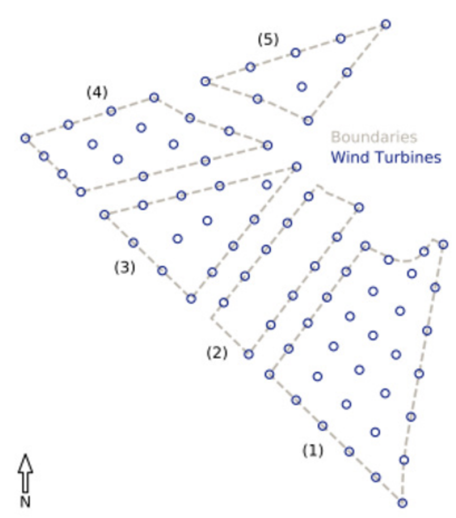

Figure 6: An overhead view of the wind farm used for the case study, including the provided example wind farm layout. Numbers in parentheses indicate region numbers. Wind turbine markers' diameters are the rotor diameters.

$$\frac{\Delta V}{V_\infty}=\left\{\left[1-\sqrt{\frac{C_T}{8\frac{\sigma_y^2}{d^2}}}\right]exd\left(-0.5\left[\frac{\Delta y}{\sigma_y}\right]^2\right), if\,\Delta x>0\right\}$$

where ΔV is the velocity deficit, V∞ is the wind velocity without wake losses, $C_T = 8/9$ is the constant thrust coefficient, d = 198 is the rotor diameter, Δy is the distance from the center of the wake to the point of interest perpendicular to the wind direction, Δx is the distance from the turbine generating the wake to the point of interest in the wind direction, and σ_y controls the width of the wake. The value of σ_y is calculated as

$$\sigma_y = k_y \Delta X + \frac{d}{\sqrt{8}}$$

where k_y is a tuned variable based on turbulence intensity. We used $k_y = 0.0324555$ based on a turbulence intensity of 0.075 (Niayifar and Porté-Agel, 2016; Baker et al., 2021). The individual wake calculations were combined using the square-root-of-the-sum-of-the-squares method (Katic et al., 1986).

$$\left[\frac{\Delta V}{V_\infty}\right]_{total}=\sqrt{\sum_{k=1}^{N_T}\left[\frac{\Delta V_k}{V_\infty}\right]^2}$$

Where N_T is the number of wind turbines.

Methodology for optimization of collinear turbines The influence of speed and design characteristics on the energy efficiency of collinear windturbines is considered. The model is based on the Blade Element Momentum Method (BEM) [12], specially modified for optimization purposes based on the criterion of maximum extracted power.Aerodynamic model An elementary ring with area dA = 2πzdz stands out from the working section of the wind wheelby two concentric circles with radii z and z+dz. This ring on the blades stands out as elementarysegments of length dz. Streamlines are drawn through both circles, forming two bottle-shaped surfaces The design of a wind farm involves a lot of (possible conflicting) optimization problems. In this paper, we haveconsidered the goal of maximizing the energy output underthe consideration of wake effects as well as minimizing thelayout costs incurred due to the turbines and the land area used. We designed strategies to overcome the infeasible solutions inthe search space and developed a particle swarm optimizationalgorithm that is able to deal with this complex multi-objectiveoptimization problem. Our approach was tested on a 200turbine layout problem. The results give new insights intothe trade-off of these two optimization goals and presentmultiple competent layouts. Multiple competent layouts areuseful in wind farm design since often many constraints andobjectives are not expressed prior to the optimization.

Ouralgorithm can be easily used as a tool for helping designers totrade-off these conflicting goals. Further studies should takeinto account other relevant optimization goals such as cablelengths, electrical subsystems and infrastructure costs. Several sites were identified as exhibiting wind potential that could be consideredpromising for electricity generation with wind speed reaching values as high as 9.5 m/s; these are located at the south and south-western parts of the area under investigation, theiroverall suitability, however, should be assessed by an integrated approach that takes intoaccount multiple constraints and evaluation criteria. The proposed framework establishesenvironmental, social, administrative, and technical constraints and combines them withtopographic, technical, and economic criteria in order to propose particular sites that areoverall appropriate for wind farms development. To this end, based on these particularconstraints and criteria, a ranking index has been established to characterize overall sitesuitability. It was found that 0.58 km2 of the Larnaca region is suitable for wind farmsiting. A sensitivity analysis on the criteria priority vectors showed that they did notaffect the results significantly; nonetheless, the wind resource potential was the mostimportant factor determining site appropriateness. Under a more balanced approach tocriteria weighting, however, suitable sites obtain better evaluation. Based on this analyzed and interpreted information, one may advocate that theprocess of sitting wind turbines from a technical point of view is quite objective. Inthe real world, however, social processes that are unfolded during the planning stagebring in a subjective element in the decision process. In order to tackle this issue, themethodological framework developed in this study, offers a solid and comprehensive basis [16-23].

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