Analysis of the comparative efficiency of wind power plants based on the geographical location and climatic conditions

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Abstract. The analysis of the comparative efficiency of wind power plant based on the geographical location and climatic conditions is considered. It is shown that in geographically remote areas, where fuel delivery is not economically profitable, it is possible to use wind power plants aimed at generating heat energy. Preconditions for the use of wind power plants for heating water and heating buildings are presented, which are associated with the possibility of energy storage in the form of hot water. Therefore, the input parameters of the wind power plant model were considered taking into account the heat storage unit. The Installed capacity utilization factor is adopted as a criterion for the efficiency of the wind power plant, which determines the ratio of the energy actually generated by the device for a certain period to the maximum possible. This is the energy that can be generated if the wind power plant operates at 100% power for a given period of time. This coefficient shows how loaded the wind power plant is in a given climatic zone. Installed capacity utilization factor is calculated for each wind station separately, depending on its geographical location and the technical indicators of the wind station itself. The DEA method was used to analyze the comparative efficiency of the wind power plants and its advantages were shown, such as the absence of restrictions on the units of measurement, as well as the fact that the efficiency can be determined only on the basis of data from the sample. In the analysis, a modification of the DEA method was used, which makes it possible to take into account the climatic zone of the location of the wind power plant. This directly affects the efficiency of both thermal and electrical energy generation. A web application has been developed for calculating the comparative efficiency of thermal power plants through the user interface using a modified DEA method, which reduces the time and improves the quality of periodic calculations for the person who makes decisions about the geographical location of wind power plants.

1. Introduction
A wind power plant (WPP) is a set of interconnected equipment designed to generate electricity using the force of the wind [1-7].
The main part of WPP is wind turbine. Structurally, this component consists of a wind motor, a system for transmitting wind power to a load (consumer) and the consumer of wind energy itself [2].

The wind turbine converts wind energy into mechanical energy of the wind motor movement. The main such movement is a circular rotary movement.

A device that directly perceives wind loads and converts the kinetic energy of the wind into rotational motion is called a vane system or wind wheel.

The wind wheel is designed in various configurations. The wind wheel consists of blades, which in turn generate torque. WPP's modern wind wheel is designed in the form of rigid blades. The cross-section is in the form of an airfoil. Also, such blades are called "wing". There are WPPs that use rotating cylinders instead of a propeller-driven propeller. There are modifications of the wind wheel made in the form of a sail system (flexible surfaces).

The vane system can differ in the axis of rotation and have either a horizontal or a vertical axis. Accordingly, according to GOST [4], a horizontal-axial wind turbine is a wind turbine whose axis of rotation of the wind turbine is parallel or almost parallel to the wind speed vector (figure 1) [7].

![Diagram of a horizontal-axis wind turbine](image)

1 – wind motor, 2 – nacelle, 3 – multiplier, 4 - load (generator), 5 – tower, 6 - foundation.

**Figure 1.** Structural diagram of a horizontal-axis wind turbine.

**1.1. Wind power plants aimed at generating thermal energy**

In remote areas, where fuel delivery to which, from the economic point of view, may be too costly, it is possible to use wind turbines to heat water and heat buildings [5]. The prerequisites for this are:

- Wind energy is not constant. As a consequence of this, short-term power changes can be discharged as ballast and supplied to the accumulators of heat storage devices. By using the
storage capacity of the heated buildings, longer power surges can be smoothed out. With a prolonged absence of wind, accumulating devices can be included in the work.

- Energy storage in the form of hot water. Also, water heating elements are undemanding to the quality of electricity.

Based on the above points, it can be concluded that when designing thermal power generation complexes, wind turbines of the simplest and fairly cheap structures can be used.

The presence of a wind-diesel and boiler plant in the power supply scheme allows for the discharge of substandard or excess electricity from the wind turbine and plays the role of a damper load in the control system of the wind turbine generator [6].

Due to the fact that the schedules of generation and consumption of electricity often do not coincide, the accumulation of most of the electricity is impossible due to the limited electrical capacity of the batteries. Therefore, the surplus has to be diverted to the ballast resistance [7].

2. Method

Based on the information presented in [8], the authors considered the input parameters of the WPP model, taking into account the heat storage unit. It is shown that we have a certain set of data (inputs), as well as one or several indicators (outputs) of the result of the operation of the set of input data of the installation. However, in order to fully understand whether our installation is effective, we have nothing to compare it with. Following from this, we also will not be able to give recommendations for improving the installation for its more efficient operation.

In [8-14], the authors showed that the DEA method allows one to estimate a large number of input and output parameters in a vector representation and that this method is the most suitable method for assessing the comparative efficiency of wind turbines in comparison with a number of parametric ones (DFA - Distribution Free Approach, SFA - Stochastic Frontier Analysis) and nonparametric (FDH - Free Disposal Hull Analysis, Malmquist Productivity Index, Tornqvist Productivity Index, Fisher Productivity Index) methods.

2.1. Installed capacity utilization factor

The so-called Installed capacity utilization factor (ICUF) is taken as a criterion for the efficiency of WPP.

Installed capacity utilization factor is the ratio of the energy actually generated by the device for a certain period of time to the maximum possible, that is, the energy that can be generated if the WPP operates at 100% power for the entire given period of time [7]. This coefficient shows how energetically WPP is loaded in a given climate zone.

The ICUF of any generating device depends on:

- from the required power consumption, which changes over time from zero to the maximum value;
- on the number and time of stopping the station, for example, for service.

For WPP, in addition, this coefficient depends on:

- from wind speed;
- from the repeatability of the wind.

The average ICUF of small wind turbines is from 0.05 to 0.15, and of large ones - from 0.15 to 0.4. ICUF is calculated using the following formula [4]:

\[
ICUF = \frac{W}{P_{nom}T}
\]
where \( W \) is the maximum energy production of the wind turbine during the time \( T \), kW ∙ h; \( P_{nom} \) – rated power of the wind turbine, kW.

To calculate according to this formula, it is necessary to determine the maximum energy production. However, the measurement process sometimes takes several years, so there is a calculation method that allows you to estimate this value, based on the differential frequency of wind speed in gradations for different climatic zones.

### 3. Results

The input-oriented DEA model [8] will take into account the climatic factor using the ICUF input for the model outputs. Based on the above, the problem statement is as follows:

\[
\begin{align*}
\min_{\theta, \lambda}(\theta), \\
-y_i u_i + y \lambda & \geq 0, \\
\theta x_i - X \lambda & \geq 0, \\
\lambda & \geq 0 \\
u_i^j & \geq 0
\end{align*}
\]

where \( u_i^j \) – dimension matrix elements \( M \times N \), there are climate-sensitive ICUF’s for outputs \( y_i \) of model DEA; \( \theta \) – an indicator of the technical efficiency of the WPP, taking into account the climatic factor; \( \lambda \) – is a vector of constants of dimension \( N \times 1 \).

Coefficient matrix elements \( u_i^j \) used in columns \( u_i \) when finding the efficiency indicator of each wind station, and are calculated from the matrix \( P \), which is the ICUF’s matrix for an object in a certain climatic zone:

\[
u_i^j = ICUF_i^j
\]

where \( ICUF_i^j \) – element of the matrix of calculated ICUFs for each object in a certain climatic zone.

#### 3.1. Territory analysis

Territory analysis is carried out in order to determine the main climatic indicators of the territory that affect the assessment of the effectiveness of WPP. This is mainly wind speed. To determine this indicator, it is necessary to use the data of the wind inventory. Wind cadastre, in accordance with GOST R 51237-98 “Non-traditional energy. Wind power. Terms and definitions” is a systematized collection of information characterizing the wind conditions of the area, compiled periodically or through continuous observations and makes it possible to quantify wind energy and calculate the expected generation [7].

After clarifying the climatic zone of the wind turbine location, it is necessary to determine whether the DEA base model is suitable. If the basic climatic conditions are the same, then the baseline model is suitable for calculating efficiency. If not, then you need to go to the calculation of ICUF’s for each WPP assessed.

#### 3.2. ICUF calculation

ICUF is calculated for each station separately, depending on its geographical position and technical parameters of the station itself in accordance with [8] and the algorithm described in [9]. Also, as a rule, to simplify the calculation, there are averaged ICUF’s for certain stations at different time intervals.
After the calculation, the ICUF’s matrix is filled for each object, depending on the climatic zone. Further, the calculation is performed using the modified DEA method.

4. Conclusion

As a result of the work done, the goal set in the study was achieved by developing a model-algorithmic support for a web application, which makes it possible to more conveniently and quickly calculate the effectiveness of WPP.

The DEA method was used to analyze the effectiveness and its advantages were shown, such as the absence of restrictions on the units of measurement, as well as the fact that the effectiveness can be determined only on the basis of data from the sample.

Also, a modification of the DEA method was proposed, which allows taking into account the climatic zone of the WPP location, which directly affects the efficiency of heat and electricity generation, by entering ICUF’s into the calculation. This modification makes it possible to obtain a more accurate assessment of the efficiency of the wind stations.

The web application developed by the authors allows the calculation of the station efficiency through the user interface using the modified DEA method, which reduces the time and improves the quality of the periodic calculations of the station efficiency for the decision maker.

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