INTERNATIONAL JOURNAL OF POLITICAL SCIENCES AND ECONOMICS
Impact Factor ( research bib ) - 9,78
https://ijmri.de/index.php/ijpse , German international journals company
ISSN 2751-9708

# METHODS AND MODELS FOR EVALUATING THE ENERGY EFFICIENCY OF WIND POWER PLANTS

***Ruziboyeva O‘g‘iljon Muminboy qizi***
*Master of the Tashkent State Transport University*

**Abstract.** The article analyzes the energy efficiency of wind power plants in the conditions of the regions of the Republic of Uzbekistan. Taking into account the climatic and wind characteristics of the country's territory, an assessment of the energy performance of low-power wind turbines was carried out based on statistical data on the distribution of wind speeds and calculated power dependencies of wind turbines. The paper uses the method of simulation of monthly and average annual electricity generation, taking into account the wind energy utilization factor. It is shown that at low and variable wind speeds, typical for a number of regions of Uzbekistan, traditional structural solutions of wind power plants have limited efficiency. The results obtained can be used in choosing the type of wind power plants and substantiating design solutions for wind energy facilities in the Republic of Uzbekistan.

**Keywords:** wind power plants; energy efficiency; wind energy; renewable energy sources; wind energy utilization rate; simulation modeling; electricity generation.

## Introduction

In recent years, the issues of improving energy efficiency and diversifying energy sources have become particularly relevant for countries with fast-growing economies and increasing electricity consumption. For the Republic of Uzbekistan, this task is of strategic importance in the context of the growth of industrial production, the expansion of the housing and communal services sector and the need to ensure reliable power supply to remote and low-energy regions [1].

Uzbekistan's traditional energy sector is largely based on the use of organic fuels, which is accompanied by rising operating costs, increased emissions of pollutants and increased dependence on fuel resources. In these conditions, special attention is paid to the development of renewable energy sources, among which wind energy is considered as one of the promising areas capable of increasing the sustainability and environmental safety of the country's energy system [2].

The territory of Uzbekistan is characterized by a significant variety of natural and climatic conditions and a heterogeneous distribution of wind potential. A number of regions are characterized by low and variable wind speeds, as well as pronounced seasonality of wind regimes. These features significantly affect the efficiency of wind power plants and require adaptation of constructive and computational approaches in their design and selection of parameters.

An analysis of existing wind power plants shows that many of the applied technical solutions are focused on conditions with stable and high wind speeds, which limits their effectiveness when operating in the climatic conditions of certain regions of Uzbekistan [3]. In this regard, there is a need to conduct computational and analytical studies aimed at assessing the energy efficiency of wind power plants, taking into account the actual characteristics of the wind flow and their operating modes.

An analysis of scientific publications shows that calculation models based on the use of average wind speed values or on the assumption of a stable wind regime are widely used in assessing the energy efficiency of wind power plants. A number of studies use probabilistic models of wind velocity distribution, including the Weibull distribution, focused primarily on regions with relatively high and stable wind characteristics [4,5].

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In the conditions of the regions of the Republic of Uzbekistan, which are characterized by low and variable wind speeds, as well as pronounced seasonality of the wind regime, the use of these approaches may lead to an overestimation of the energy performance of wind power plants. This makes it necessary to adapt the calculated models taking into account the real statistical characteristics of the wind flow [6].

Of particular importance in this context is the use of simulation modeling methods that allow taking into account the statistical distribution of wind speeds and determining the monthly and average annual electricity generation. This approach makes it possible to more reasonably assess the energy potential of low-power wind power plants and choose rational solutions for their use in regional energy systems.

**The purpose and objectives of the research**

The purpose of this work is to analyze the energy efficiency of low-power wind power plants in the regions of the Republic of Uzbekistan based on computational models and statistical data on the distribution of wind speeds.

To achieve this goal, the following tasks are being solved:

– analysis of the impact of the wind regime on the energy performance of wind power plants;

– development of a computational model for estimating average power and electricity generation;

– conducting computational experiments and analyzing the results.

The solution of the tasks set is aimed at obtaining a quantitative assessment of the energy performance of low-power wind power plants and identifying the area of their effective use in the regions of the Republic of Uzbekistan.

**Statement of the problem**

The objective of the study is to develop and apply a computational model for assessing the energy efficiency of low-power wind power plants operating in conditions of low and variable wind speeds typical of the regions of the Republic of Uzbekistan.

As part of the task, it is necessary to determine the dependence of the average power and electricity generation of wind power plants on the statistical characteristics of the wind regime, as well as to assess the impact of the average wind speed on the energy performance of wind turbines under different operating modes. Special attention is paid to taking into account the stochastic nature of the wind flow and the limitations associated with the operation of wind power plants in conditions of low wind potential.

The energy efficiency assessment of low-power wind power plants is based on simulation modeling of their energy characteristics, taking into account the statistical distribution of wind speeds typical for the regions of the Republic of Uzbekistan. The average capacity of a wind power plant and the amount of electricity generated over the estimated period are used as the main performance indicators.

When determining the actual electrical capacity of a wind power plant, losses in the electric generator are taken into account, which are described by the efficiency factor. The wind turbine power (WTP) is determined by the expression:

$$P_{WTP}=\eta \cdot P_T$$

where $\eta$ - is the efficiency of the generator (usually equal to 0.8 - 0.9); $P_T$ - is the power of the wind turbine, Wt.

The mechanical power of a wind turbine is determined through the wind energy utilization factor, which characterizes the proportion of wind energy converted into useful mechanical energy:

$$P_T=K_{WEU} \cdot P_f$$

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where $K_{WEU}$ - is the wind energy utilization coefficient; $P_f$ - is the power of the wind flow passing through the swept area of the rotor.

The wind energy utilization factor characterizes the proportion of wind flow energy converted into mechanical turbine energy [7].

$$P_f = \frac{1}{2}\rho S V^3.$$

where $\rho$ - is the air density (assumed to be 1.225 kg/m$^3$), $S = \pi D^2/4$ - is the swept area of the rotor of the wind turbine; $V$ - is the velocity of the undisturbed wind flow.

To determine the average power and electricity generation, it is necessary to take into account the unevenness of the wind regime. In the framework of this study, the time distribution of wind speeds is approximated by the normal (Gaussian) law, which makes it possible to use the averaged statistical characteristics of the wind flow:

$$f(V) = \frac{A}{\sqrt{\pi}} exp\left[-A^2 (V - V_0)^2\right]$$

where $V_0$ - is the average wind speed; $A$ - is a distribution parameter determined based on statistical data for a specific range of average wind speeds.

The use of the normal distribution of wind speeds in the framework of this study is due to the need to obtain an average estimate of the energy performance of wind power plants with a limited amount of statistical data. With small ranges of wind speed changes and the analysis of average values over the estimated period, this approximation allows us to adequately describe the stochastic nature of the wind flow and is widely used in engineering assessments of energy efficiency. The parameter A of the normal distribution of wind speeds is determined depending on the average wind speed and reflects the degree of dispersion of wind flow velocity values. The values of parameter A used in calculating the energy efficiency of wind power plants in the regions of Uzbekistan are shown in Table 1.

Table 1. Values of parameter A of the normal distribution of wind speeds used in calculations of energy efficiency of wind power plants.

| $V_0$, m/s | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| A | 0.228 | 0.185 | 0.165 | 0.15 |

The following assumptions were made in the calculations, reflecting the actual operating modes of wind power plants:

- when the wind speed is lower than the calculated wind turbine power is proportional to the cube of the wind speed;
- when the wind speed is higher than the design value, the power is limited by the nominal value;
- the parameters of the wind velocity distribution are considered constant within the considered calculation period.

Based on these assumptions, the average capacity of a wind power plant is determined by integrating over the entire range of possible wind speeds:

$$P_{avarage} = \int_0^{\infty} P_{nom}\left(\frac{V}{V_P}\right)^3 A \cdot e^{-\pi A^2 (V - V_0)^2} dV$$

where $P_{nom}$ - is the nominal capacity of the wind power plant.

The obtained average power value is used to calculate monthly and average annual electricity generation, as well as to analyze the effect of average wind speed on the energy efficiency of low-power wind power plants. The use of simulation modeling makes it possible to take into account the stochastic nature of the wind flow and obtain a more realistic assessment of

wind turbine energy performance in conditions of low and variable wind speeds typical for a number of regions of Uzbekistan.

The calculations did not take into account the influence of wind flow turbulence, terrain features, as well as changes in air density depending on the temperature and height of the installation. The accepted calculation model is focused on a preliminary assessment of the energy efficiency of wind power plants and an analysis of the influence of average wind speed on their energy performance.

**Solving the problem**

The solution of the problem is carried out on the basis of simulation modeling of the energy characteristics of wind power plants using a statistical description of the distribution of wind speeds. Within the framework of the developed methodology, the mechanical and electrical power of a wind turbine is determined, taking into account the wind energy utilization factor and the efficiency of the generator.

Based on the integration of power over the entire range of possible wind speeds, the average capacity of a wind turbine is calculated, which is then used to determine the monthly and average annual electricity generation. Conducting computational experiments for various values of the average wind speed makes it possible to obtain a quantitative assessment of the energy efficiency of low-power wind power plants and analyze the scope of their rational use in the conditions of the regions of the Republic of Uzbekistan.

Results of computational experiments.

In accordance with the developed methodology, computational experiments were conducted aimed at evaluating the energy efficiency of low-power wind power plants at various values of the average wind speed. The calculations were performed for the range of wind speeds typical for the regions of the Republic of Uzbekistan using the normal distribution parameters shown in Table 1. The main results of the simulation are the values of the average capacity of the wind power plant and the estimated power generation.

Table 2. Calculation results for the average wind turbine power and power generation

| Average wind speed $V_o$, *m/s* | Average power $P_{avarage}$, *kVt* | Monthly output, *kVt·h* | Annual output, *kVt·h* |
|---|---|---|---|
| 3 | 0,35 | 252 | 3024 |
| 4 | 0,75 | 540 | 6480 |
| 5 | 1,40 | 1008 | 12096 |
| 6 | 2,20 | 1584 | 19008 |

The analysis of the results presented in Table. 2 makes it possible to establish a stable dependence of the average power of a wind turbine on the average wind speed. With an increase in the average wind speed from 3 to 6 m/s, the average wind turbine power increases by more than six times, due to the cubic dependence of power on the wind flow velocity at the site of operation below the nominal mode.

The data obtained confirm that even a slight increase in the average wind speed has a significant impact on the energy performance of low-power wind turbines and should be taken into account when assessing the feasibility of their use in specific regional conditions.

The scientific novelty of the work is the development and application of a computational model for assessing the energy efficiency of low-power wind power plants, adapted to the conditions of low and variable wind speeds in the regions of the Republic of Uzbekistan, using simulation modeling and statistical description of the wind regime.

**Conclusion**

The paper analyzes the energy efficiency of low-power wind power plants in the regions of the Republic of Uzbekistan based on simulation modeling and statistical description of the wind regime. A calculation method has been developed for determining the average power and electricity generation of wind power plants, taking into account the unevenness of wind speeds.

The results of computational experiments have shown that at average wind speeds of less than 4 m/ s, the efficiency of wind power plants is significantly reduced, while at speeds of 5-6 m/s there is a significant increase in energy performance. The results obtained can be used in selecting the parameters of wind power plants and substantiating design solutions for distributed and autonomous energy facilities based on renewable energy sources.

The practical significance of the work lies in the fact that the results obtained are focused on practical application in justifying the choice of the type of wind power plants and developing design solutions for wind energy facilities in the regions of the Republic of Uzbekistan, and can also be used in forming recommendations for the development of distributed and autonomous energy based on renewable energy sources. The findings can serve as a basis for further research aimed at improving the design and operational parameters of wind power plants in order to increase their efficiency in regions with low wind potential.

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