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Methodology to evaluate the placement of wind turbine based on GIS technology

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Abstract. The paper is devoted to the development of a methodology to evaluate the possible locations of wind generators using GIS technologies for the climatic conditions of the Western Urals. A model of the wind generator operation in the electrical network using the OpenModelica simulation environment has been built. Recommendations on the use of a wind generator and a feasibility study of its use on the base of an energy-efficient autonomous research module (EEARM) are worked out.

1. Introduction

One of the research areas directions within the concept of urban sustainable development is the use of renewable energy sources (RES) [1, 2]. The most sought-after renewable energy sources in the world include: solar energy, wind energy, water energy (including wastewater energy), tidal energy, wave energy and water bodies, including water bodies, rivers, seas, oceans, geothermal energy with using natural underground heat carriers, low-potential thermal energy of the earth, air, water using special heat carriers, biomass, including plants specially grown for energy, including trees, production and consumption waste, biogas, gas emitted from production and consumption wastes at landfills for such wastes, gas generated from coal mining.

The Perm Ktai as well as many other cold regions, generates the vast majority of energy from traditional resources. However, taking into account the climatic features of the territory, including low solar activity, high rainfall, high duration of snow cover during the cold seasons, the study of promising locations of wind generators becomes relevant.

It is known that the introduction of wind generators will contribute to a significant reduction in harmful emissions from fuel combustion. As an example, a wind generator with a capacity of 1 MW reduces annual emissions to the atmosphere: by 1,800 tons CO_2, by 9 tons SO_2, and by 4 tons NO_x. Given the wide distribution of wind turbines in countries with low average annual air temperatures, the question of determining the appropriate installation sites in the conditions of the Western Urals has not been resolved.

In order to conduct the RES researches at Perm National Research Polytechnic University (PNRPU) in cooperation with the Ministry of Industry of Perm Krai, a project of the creation of the energy-efficient autonomous research module (EEARM) with a GHP and a building dispatching system was developed and implemented, is a one-story office building, equipped with a system of dispatching and management of the smart home energy system [3].

2. Climatic assessment of the territory for the wind generator placement

The Perm climate is moderate continental. The increased humidity is due to the location on the river and the proximity of the Kama Reservoir. The average annual temperature ranges from +1.0 to +1.2 °C, the average July temperature is +17.6 °C, and the average January temperature is -15.7 °C. Annual rainfall ranges from 410–450 mm in the southwest of the region to 1,000 mm in the extreme northeast points of the region.

To determine the average wind speed, data from the electronic resource rp5.ru were taken and analyzed from station 28224 for Perm in the period January 1, 2005 – June 20, 2017, Figure 1.

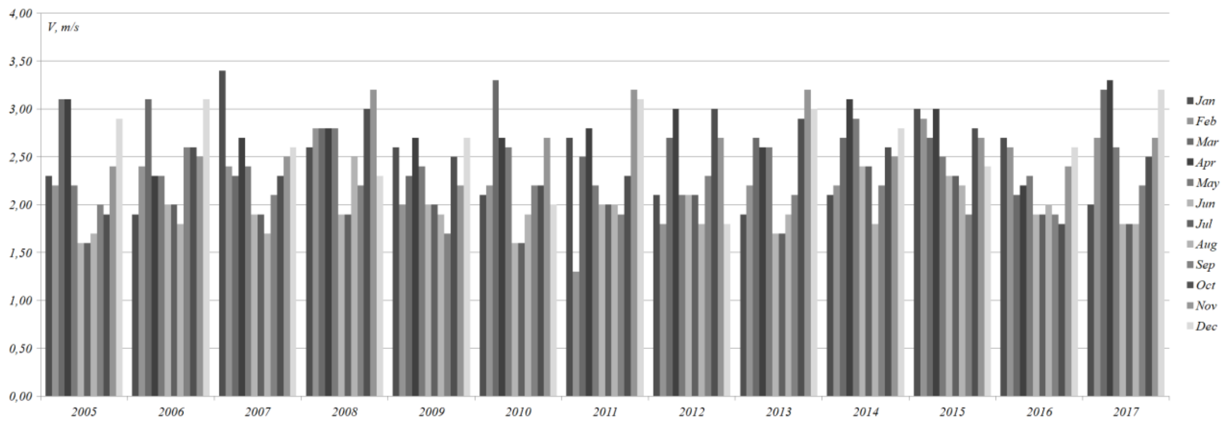

Figure 1. Wind speed data by month for Perm, m/s

According to the study, the average annual wind speed for 2017 was 2.6 m/s. The minimum wind speed occurs in the summer months. The highest wind speeds are observed in the winter, as well as in the transitional seasons – spring and autumn. According to the wind roses, the prevailing wind directions in winter are southern and south-western, and in summer, northern and north-western, western. Since in the winter period the wind is much stronger than in summer, it is preferable to consider the south-west direction as receiving more energy.

3. Study methods for the of promising territory for the wind generator installation

To solve the problem of finding the optimal locations for the installation of a wind generator, a study using special ArcGIS software of ESRI company was conducted. Description of the method:

1) Download a raster image of the relief from the site «Viewfinder Panoramas», http://www.viewfinderpanoramas.org. It is selected specifically for study territory.

2) Creating the slopes` exposure of all directions using built-in tools.

3) Creating the slopes exposure of the most leeward direction, in this case – the south-west wind direction. Using the «Raster Calculator» tool. The tool allows selecting the desired slopes` exposure. The selection of the desired slope exposure depending on which is leeward. In the Perm climatic conditions, the exposure of the southwestern slopes is the most promising, because in a given direction the wind has a more frequent recurrence.

4) Convert raster to vector. Convert the resulting raster into a vector using the «Raster to object» tool. Conversion is necessary for more convenient work with the map and subsequent data processing.

5) Loading shapefiles. The shapefiles are loaded from the NextGIS site, http://data.nextgis.com. Shape files are an Esri vector data format for storing information about the location, shape, and attributes of geographic features. Shape files contain information about roads, buildings, forests, water bodies, territorial boundaries and other objects.

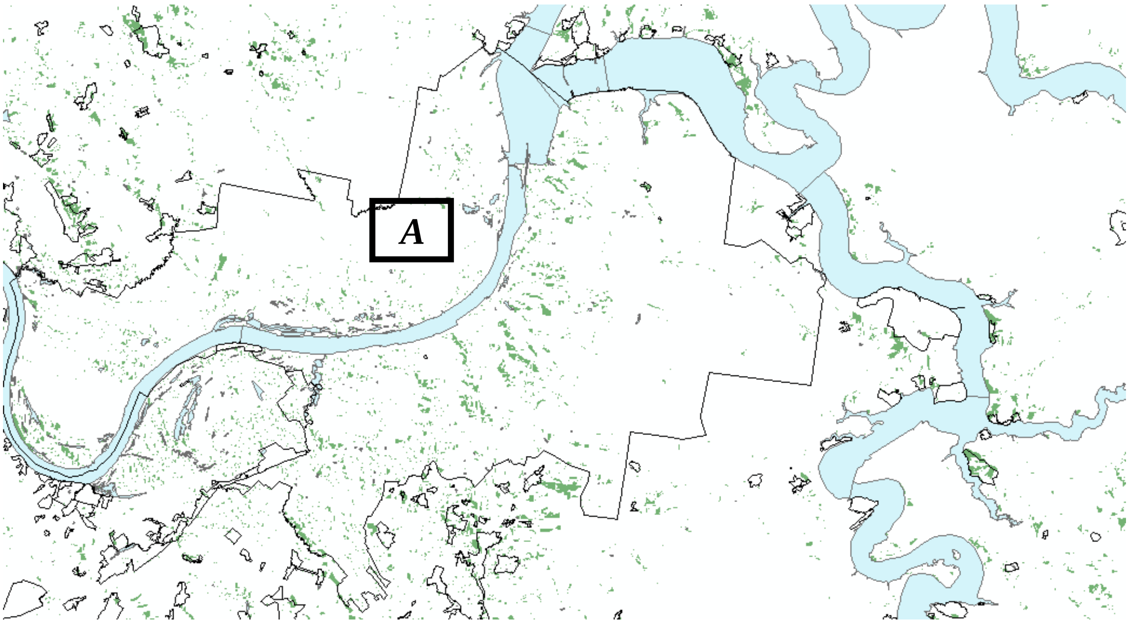

Figure 2. Slopes` exposure of the south-west direction with possible locations for the installation of wind generators

6) Creating the slopes exposure of the south-west direction with possible places to install a wind generator. Remove all elements on which the installation we of wind generators is not allowed with the help of a special option «attribute table». The obtaining of the slopes` exposure of the south-west direction with optimal locations for the wind generator installation (Figure 2). The figure shows the possible locations of wind generators, marked in dark green. It is advisable to place wind power plants on these sites, as the wind has the greatest intensity and considerable potential.

4. Technical and economic assessment of the wind generator use at the energy-efficient autonomous research module (EEARM)

At the Perm National Research Polytechnic University (PNRPU) in cooperation with the Ministry of Industry of Perm Krai, a project of the creation of the energy-efficient autonomous research module (EEARM) was developed. The module is equipped with a wind generator and building monitoring and control system [4]. The module is single-storey office center with the total area of 200 m^2. It contains personal computers, office equipment, heating, air conditioning, ventilation, lighting, and access control systems. EEARM is used to develop field experiments on the use of renewable energy sources, including wind generators, in the climatic conditions of the Western Urals [1].

As a rule, Perm consumers consider that it is not profitable to install wind generators due to their large initial investments and insufficient information on payback periods. This is also due to the fact that the forest and buildings will be obstacles to the wind flow, thereby reducing its speed. For the study area, see Figure 2 block A, the method of finding the optimal locations of the wind generator was applied and the slopes exposure of the south-west direction was obtained. Plots were found for this territory for optimal locations of the wind generator.

1. Determination of the required power of the wind generator [5]:

- The amount of power consumption of all devices EEARM E_{day}:

$$E_{day} = \sum P_i \cdot T_i = 13.97 \text{kW·hour} \quad (1)$$

where P_i – installed capacity of i-th consumer, kW;
T_i – usage time per day of the i-th consumer, h;

- Taking into account the demand factor K_d = 0.8, we obtain the calculated power consumption Ec.

$$E_c = E_{day} \cdot K_{day}, \quad (2)$$

$$E_c = 11.176 \text{ kWt·hour} \quad (3)$$

- Similarly, it is possible to calculate the necessary daily energy W_{day} for a group of buildings located near the EERAM, kW·h:

$$W_{day} = 480.568 \text{ kW·h} \quad (4)$$

- Determination of the required power of the wind generator. Energy consumption per hour is W_h, kW·h

$$H = \frac{W_{day}}{24}, W_h = 20.024 \text{ kW·h}. \quad (5)$$

2. To select the optimum height of the mast for efficient energy production, an exponential dependence of the wind speed on its height above the earth surface was used [6].

$$V_1 = V_0 \cdot (\frac{H_1}{H_0})^k, \quad (6)$$

where V_1 – wind speed at a given height, m/s;
V_0 – wind speed at a known height (for weather stations taken 10 m), m/s;
H_1 – set height, m;
H_0 – measurement height, m;
k – empirical indicator of surface roughness, k = 0,37.

Having considered the options for different locations of the proposed rotor axis of the wind generator (Figure 3), a mast height of 35 m was selected. The average annual wind speed with this mast would be 4.1 m/s. At such wind speeds and at the rotor axis` height, the wind generator will be in operation and generate electricity.

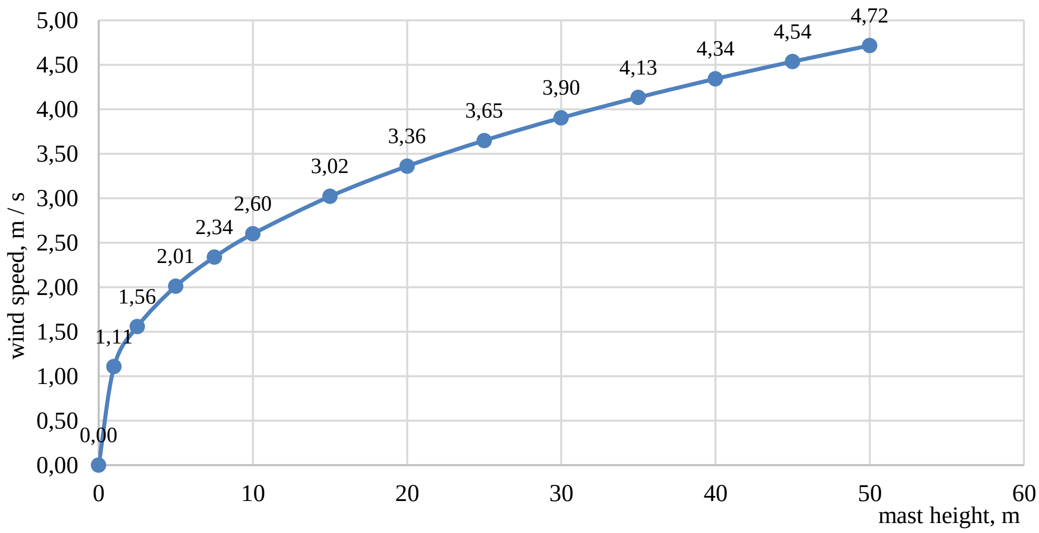

Figure 3. Changes in wind speed at different height of wind generator

3. The following is the definition of the wind generator` parameters [7]:

- Determination of the power of the wind generator power plant P_w, kW:

$$P_w = \frac{K \cdot q \cdot v^3 \cdot S}{2}, \quad (7)$$

where K – the coefficient of the wind energy use is assumed to be equal to 0.43…0.47;
q – air density, assumed to be 1.293 kg/m^3 under normal conditions;
v – average annual wind speed at a height of 35 m;
S – propeller swept area, m^2
$S = \frac{\pi d^2}{4}$,
where d – wind turbine blade diameter, m.

$$S = \frac{P_w \cdot 2}{K \cdot q \cdot v^3} = 956{,}1 \text{ m}^2 \quad (8)$$

$$D = \sqrt{\frac{4 \cdot S}{\pi}} = 35 \text{ m} \quad (9)$$

It is inadvisable to use one installation with such a large rotor diameter, then we take 6 wind generators for calculation, and the power of one wind generator P_{wg} will be equal, kW:

$$P_{wg} = \frac{P_w}{6} = 3.337 \text{ kW·h} \quad (10)$$

It is necessary to make secondary calculations and find the required diameter of the rotor of the wind generator:

$$S_w = \frac{P_{wg} \cdot 2}{K \cdot q \cdot v^3} = 159.35 \text{ m}^2 \quad (11)$$

$$d_w = \sqrt{\frac{4 \cdot S}{\pi}} = \sqrt{\frac{4 \cdot 159.35}{\pi}} = 14 \text{ m} \quad (12)$$

Thus, to supply buildings with energy around EEARM, 6 wind generators with a rotor diameter of 14 m are needed.

4. The following data was taken into account for the calculation of capital investments:

- Wind power installation Condor Air 380 – 6 pcs.;
- Lead-acid battery Delta Delta GSC 3000 – 5 pcs.;
- Inverter IS-12-4500 – 5 pcs.;
- Materials, device base, storage room for process equipment;
- Cost for the territory.
- Total capital investments are amounted to 4512994.37 rub.

5. $t_{ок} = \frac{P \cdot c + И_{exp}}{Э_к \cdot C_{ter}} = 31.2\, yaer$ Operational costs of wind generators servicing with the expectation of one structure around EEARM amounted to 2889.5 rubles per month.

6. The key factor in assessing the feasibility of the application is the value of the payback period:

- The payback period for one EEARM for the introduction of wind generators is:

where $P \cdot c$ – the total cost of the installation, taking into account the cost of the unit, transportation, customs costs, design and construction works, rub; $P \cdot c$ = 353588.3 rub.
$И_{expl}$ – exploitation costs, rub/year.
$Э_{wg}$ – electric power generated by wind generators for 1 year per 1 building, kWh / year. $Э_{wg}$ = 4079.3 $kW \cdot h$ /year
$C_т$ – electricity tariff, rub/kW·h, $C_т$ = 2.80 rub/kW·h

- The cost of energy generated by wind turbines:

$$C = \frac{P \cdot c + И_{expl} \cdot t_{sl}}{Э \cdot t_{sl}} = 4\ \text{rub/kW} \cdot \text{h}$$

where t_{sl} – wind generator service life, t_{sl} = 25 years.

The resulting payback period of the wind turbine is high. As a rule, the maximum payback period accepted for consideration is 20 years. Thus, this installation cannot be considered as commercial. However, provided it is implemented in a region with no power lines, it can be a question of improving living and working conditions, developing local infrastructure and ensuring the comfort of residents and office staff in connection with more reliable electricity generation.

Thus, this installation cannot be considered as commercial. However, provided it is implemented in a region with no power lines, it can be a question of improving living and working conditions, developing local infrastructure and ensuring the comfort of residents and office staff in connection with more reliable electricity generation.

7. In order to estimate the change in the payback period in the future, it is necessary to conduct a forecast of the change in tariffs up to 2050 based on the change in rates for previous years. Based on the change in tariffs in previous years T_i, the average change in the value of tariff Δ was calculated:

$$\Delta = \frac{(T_i - T_{i+1}) + (T_{i+1} - T_{i+2}) + \dots}{n}, \ \Delta \ = \ 0.14\ \text{rub/kW·hour}$$

On the basis of the obtained values, it should be concluded that the tariff value increases every year and in approximately 2026 it will be equal to the cost of energy received from the wind generator. Also, the value of the payback period decreases every year, and in 2023 it will be 25 years as well as the life of the wind generator, and in 2030 it will be less than 20 years, which means the economic feasibility of installation in terms of changing tariffs.

5. Modeling of the wind generator in the electrical network

To develop a model of operation of a single wind generator with calculated characteristics for the EEARM network, the OpenModelica simulation environment was used, which includes a large number of different libraries and components of electric power and mechanical systems, see Figure 4.

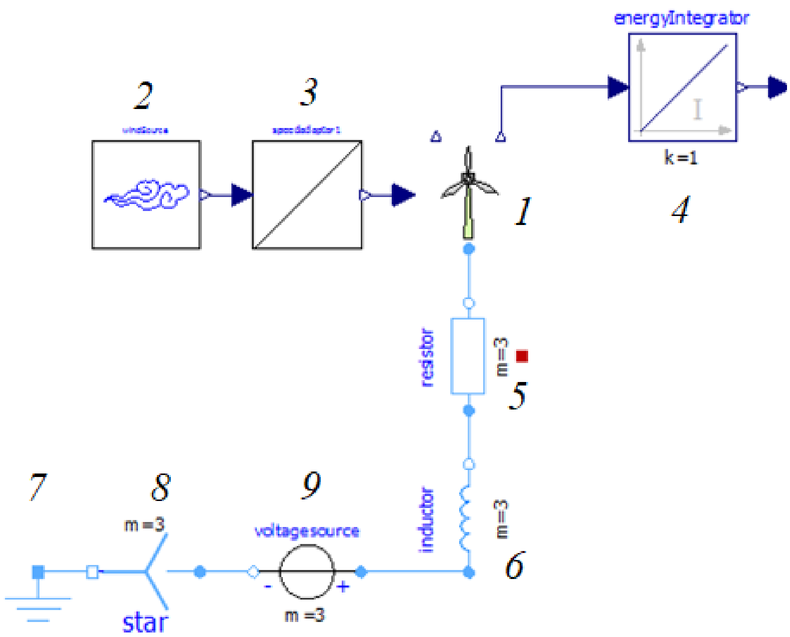

Figure 4. Model of connecting the wind generator to the network in the environment of OpenModelica

Block 1 – ideal wind power plant with a variable speed generator and electrical connection to the network. The generator is controlled in such a way that the reactive power is zero.

Block 2 – real wind speed data from file – fileName.

Block 3 – generator wind speed converter.

Block 4 – monitoring input power. Within this block calculates the amount of electrical energy from the wind generator y (element), as the integral of the input power u multiplied by the gain factor *k*.

Block 5 – three phase linear resistor. A linear resistor connects the complex voltages to the complex currents i using m single-phase resistors. The resistor model also has m additional conditional thermal indices. The linear temperature dependence of the resistance is accepted for the allowed thermal values of the indices.

Block 6 – three phase linear inductance. Linear inductance connects complex voltages with complex currents *i*, using single-phase inductances.

Block 7 – network grounding.

Block 8 – connection of a three-phase circuit using a «star circuit».

Block 9 – constant three-phase alternating voltage. This model describes m constant voltage sources, which determine complex voltages by RMS voltages and phase shifts (by default, a symmetric circuit).

The result of one-month wind generator simulation based on the data of wind speed statistics is shown in Figure 6. These results can be used when conducting energy management of EEARM as target values of electricity generation from its own sources [8].

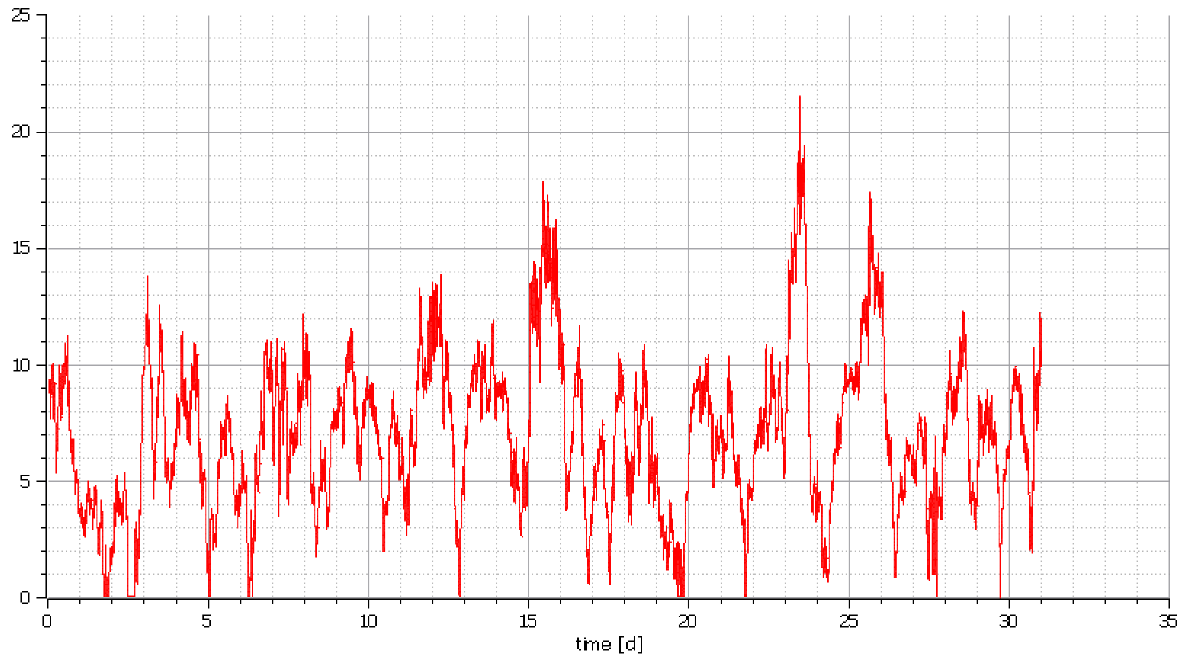

Figure 5. Simulation of power generated by the wind generator in the network during the month

6. Conclusion

Based on the results obtained, the following conclusions can be drawn:

1. Using the above method for finding the best locations for a wind generator, you can determine the locations of the most appropriate and promising facilities, you can also roughly identify potential energy consumers in the northern regions, in particular the territories of the Western Urals. This study does not take into account the dynamic effect of objects located on the site.

2. It was revealed that in the climatic conditions of Perm it is more promising to install a wind generator with an installation height of 20 m and above. Thus, the average annual wind speed will be 3.36 m/s, which will ensure the functionality of the wind power plant.

3. In the climatic conditions of the Perm region, it is recommended to install a combined power plant, including a wind generator and solar panels, which will ensure the necessary generation of electricity during a period of calm or in cloudy weather. This need is illustrated by the results of modeling the operation of a wind generator in the network.

4. The conducted technical and economic analysis showed that when a wind generator was introduced as a source of electricity for office buildings with a daily power consumption of approximately 0.5 MW·hour, the payback period would be approximately 31 years.

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