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Life Cycle Analysis of Low-Speed Multi-Blade Wind Turbine

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Abstract - The paper describes the methodology and carries out an energy and exergy-net analysis of multi-blade, low-speed, wind turbine WPI-5-4, and obtains the coefficients of energy and exergy-net conditions of several regions of The Russian Federation. It was determined that at the average wind speed in the considered area of approximately 5 m/s, the coefficients of energy - and exergy-net for the wind turbine WPI-5-4 are at the same level of performance as thermal and nuclear power plants. At higher wind speeds, these coefficients increase and begin to exceed the level of similar indicators of traditional energy power plants, reaching an average wind speed of 9.9 m/s of the exergy-net coefficient of hydroelectric power plants. The terms of energy and exergy payback for the conditions of the considered meteorological stations range from 1.06 to 9.55 and from 0.9 to 8.1, respectively. The calculations given in the paper show high exergy efficiency of wind turbines because their end product is electric power while a lot of thermal energy is spent for creation of such systems.

Keywords—Net Energy Analysis, Energy Return on Investment (Eroi), Exergy Return On Investment (Exroi), Wind Turbine.

1. Introduction

One of the most developed renewable energy technologies of today is wind power. Its principle consists of transforming kinetic wind power to mechanical energy of the rotating shaft with a possibility of its subsequent transformation to electric energy. Wind turbines find more and more broad applications in various spheres of human activities, both for continuous and emergency power supply for various consumers.

Often the decision to build the wind power plant is made based on economic analysis of the project from the perspective of obtaining maximum profits in a minimum payback period. In some cases, when building such systems, the decisive factor is a lack of alternative systems, e.g. for energy supply of the remote important consumers in places with high wind provision. In addition to economic analysis in European countries and the USA, the energy and exergy analysis of projects become more common. It shows the efficiency not from the material or financial costs point of view, but the ratio of energy in the construction and operation of the facility with the amount of energy delivered throughout the whole life cycle. It is not efficient to build the installation producing smaller amounts of energy than was spent for its construction, unless there is an acute necessity.

Analysis of this sort is especially relevant for renewable power generation installations, utilizing the energy of the sun and the wind since these sources differ in stochasticity and dispersion of energy in space. In order to capture this energy flow it is necessary to increase the size of the units, which leads to increased material consumption per kilowatt of installed capacity, which in turn leads to growth of cost of energy and exergy efficiencies for their production. This issue is particularly acute in regions with low energy potential. For Example: when using low wind speeds, it is necessary to increase the number of blades of wind turbines, which leads to increased material consumption. On the other hand, these wind generators are often have a small power rating and low annual productivity, which significantly affects the term of energy payback of the project, therefore the study of such objects is the most important.

In world practice, such an approach to study the function of the site is called the net energy analysis and its foundations were laid in [1 - 6]. Initially, whole industries, manufacturing processes and conventional energy generation installations using fossil fuels in the cycle were exposed to the analysis. Today, with the growth of the share of renewable power in the overall power balance of various countries, even more often it is possible to meet the researchers devoted to these systems. A significant part considers wind power installations [7 - 12] being the most widespread and sought-after. However, the majority of work is devoted to energy balances and does not consider the effectiveness of such systems from the point of view of exergy, whereas the use of this approach enables to assess the system taking into account “the quality” of the energy produced.

The indicators of energy efficiency of wind turbines depends on a number of parameters, in particular the place of its location, capacity, utilization rate of installed capacity. Not unimportant factor is power consumption of its production which depends on technologies of the country of the producer. Unfortunately, because of the small number of existing wind turbines in Russia similar studies carried out is not enough. In this paper we define energy consumption production and the efficiency of low-speed multi-blade wind turbine 4 kW for the conditions of the Russian Federation on a technique of net energy analysis, a comparison with other technologies, and draws conclusions about the appropriateness of this kind of installations.

2. Research Methodology

The methodology of the net energy analysis of the power installation is limited to the analysis of flows of energy and exergy through the object boundaries from the moment of making a decision on construction until the end of physical existence of the object. Prior to construction, the land plot was only terrain. In the process of creating a technical object across system boundaries, the flow of substance and energy begin to enter and upon completion of construction there is a possibility of the energy discharge at stationary operating parameters during the service life. Finally, after all of the time of operation the technical object is dismantled (with partial refurbishment of materials). The above can be reflected quantitatively, using balance of energy or exergy, scaling from flows per time unit to their full value throughout time of existence of the object, as shown on Fig. 1.

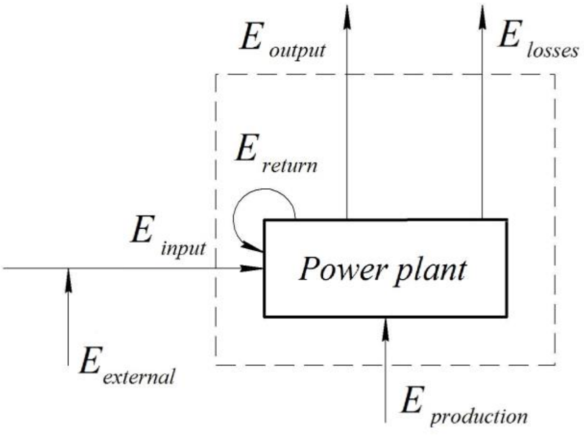

Fig 1. The flow of energy or exergy through the control surface during the lifetime of a power facility.

The history of a power facility operation is represented in Fig. 2. Since the decision was made to build a power plant to generate electricity or heat, it is not the production, but the energy consumption for the manufacturing of equipment, construction and installation work actually starts. These costs begin even before making decisions on the specific installation in connection with delivery of the standard equipment, smelting the metal for it, and construction (if necessary) of plants for the production of the equipment. Energy production begins only in some years after adopting the decision, at the time of production and proceeds for several decades until moral or physical wear of the equipment.

To carry out the analysis of the energy and exergy efficiency of the energy object, it is necessary to possess information not only regarding its performance, but also to estimate the costs which were required to create it. This requires for a methodology of such an assessment. How efficient are the processes for the procurement of materials, fabrication of parts and components? Eventually, it depends on the cost of energy needed to create the equipment of the power plant. The full intensity of the production is the quantity of consumption of energy and/or fuel in the manufacture process, including the cost of extraction, transportation, processing of minerals and production of raw materials, and additional parts that consider the utilization rate of raw materials. The energy intensity of the same product may vary considerably from one manufacturer to another and depends on many factors including the initial stock, applied technology, perfection of the equipment, logistics and many other things.

According to all researchers, the most power-consuming process in the construction of machines is the process of procuring materials, because it is associated with the extraction of primary raw materials and its subsequent processing.

The mass of the finished product determined by the total sum of the masses of parts and assembly units included in the installation and its specific weight, defined as the ratio of its dry mass to installed capacity, and does not fully characterize the material costs for the creation of the installation. These

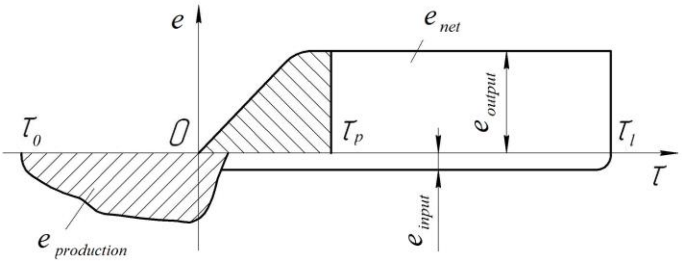

Fig 2. Variations of consumed and produced energy flows in time

indicators characterize the degree of technical perfection and rationality of design presuming significantly more than its technological rationality.

For assessing the consumption of materials and energy costs for the creation of installations of renewable energy, it is necessary to consider the weight of unfinished parts. Blank weight, depending on the characteristics of the finished part may exceed the weight of the part by several times. In the process of manufacturing a part, waste is generated, which can be considered irretrievably lost, in most cases, from the technology and energy point of view. Therefore, at the estimation of energy costs specific to the weight of finished equipment do not consider material and energy losses that occur directly in the manufacturing process, but can amount to a considerable value.

To assess the degree of the rational use of materials in engineering, the materials utilization rate is applied:

$$k_{mu} = \frac{m}{m^{w}}, \qquad (1)$$

where m is the mass of finished part, m^{w} – mass of a blank for this part. Material utilization rate is, in essence, an indicator of perfection of the production technology. It depends on the complexity of a product, mass character of production, availability of the equipment, qualification of the personnel, and other factors. In large-series production, focused on the production of specific products, the material utilization rate reaches 0.95, whereas in one-off production or in the manufacturing of pilot samples of complex products it can drop to 0.2 and lower.

Energy costs to create individual parts, assemblies as well as entire power plants can be estimated using the formula:

$$E_{inst} = k_{prod} \sum_{j=1}^{n} m_{j}^{w} \cdot E_{j} = k_{prod} \sum_{j=1}^{n} \frac{m_{j} \cdot E_{j}}{k_{mu}}, \qquad (2)$$

where k_{prod} – the correction factor, taking into account the energy cost of manufacturing of parts, assembly, transportation and depending on the technological characteristics of a particular enterprise, E – energy costs for the production of material. By a similar formula, the cost of exergy can also be calculated for the creation of the power plant. The accuracy of calculations by eq. (2) increases with the increase of the level of detailing from the power plant as a whole to specific parts and units. In addition, when using this formula the concealed losses associated with the technological features of production of the product are considered.

During its life cycle, from the design stage to the time of decommissioning, any power plant does not only produce but also consumes energy. The integrated chart of energy costs is shown in fig. 3.

The listed expenditure items are common to all power plants, but with renewable energy sources, some of them may be missing or may be substantially lower, compared to traditional energy plants.

The first is the costs of fuel provision, which is not typical for wind power engineering, since power plants of this type are located in places where there is a wind potential. In such systems the energy costs for own needs are quite low, because the cycle of their operation does not require transfer of large volumes of heating agent, as is the case in thermal power stations. During operation of wind turbines, the costs for waste disposal are minimized, since their operation is not associated with burning of the organic and the disintegration of nuclear fuel and, as such, harmful emissions are absent. There are only costs for the disposal of waste lubricants, consumables, etc., but these costs are negligible compared with the traditional energy installations. The costs of human energy in the operation of wind turbines are also quite low. With the modern development of science and technology, the renewable energy plants tend to be automated and autonomous to the maximum extent, functioning without human presence. Energy costs for the disposal of wind turbine plants are reduced mainly to dismantling and transporting them to the processing site and

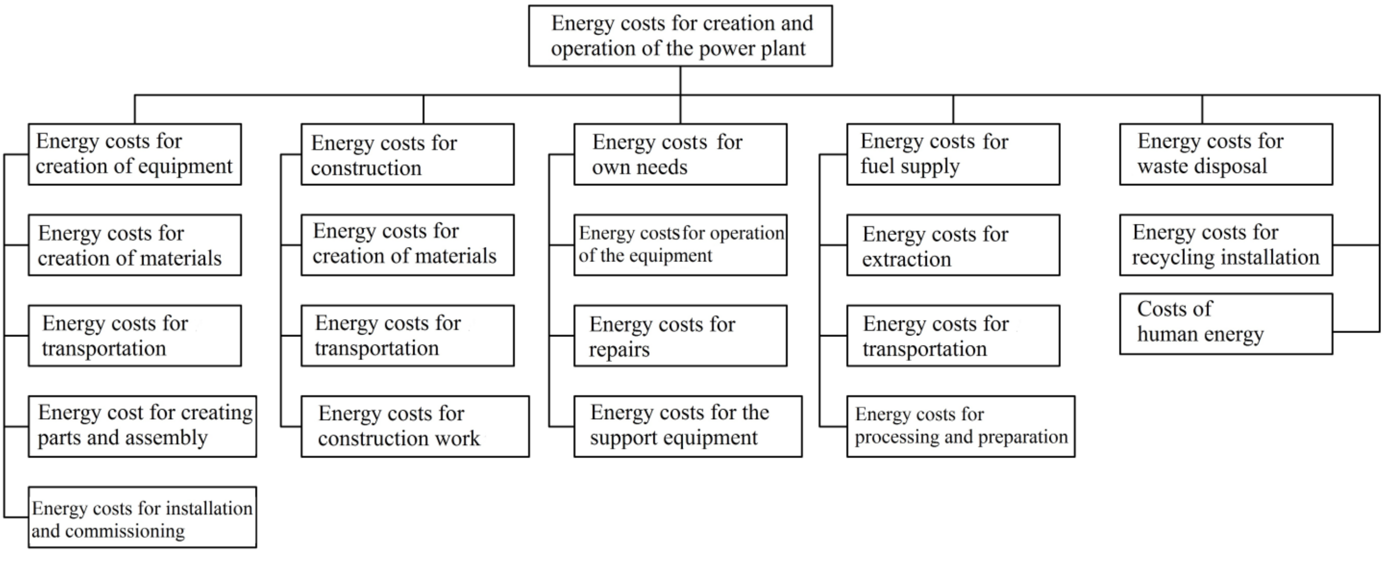

Fig.3. The structure of the energy costs during the establishment, operation and decommissioning of the energy facility.

are not associated with any complex technical operations, such as for nuclear power equipment. Therefore, this cost item does not play a significant role in the overall energy balance either.

Thus, the main areas of expenditure of energy in the creation and operation of wind turbines are the production costs of equipment and civil engineering. Moreover, for smaller systems, the construction of any objects is often not required, so this cost is not always present.

To carry out energy and exergy net analysis it is necessary to summarize all costs of energy and exergy needed for the power plant operation given on Fig. 3. using the formula:

$$E_{input} = \int_{\tau_p}^{\tau_l} e_{input}\, d\tau \,, \tag{3}$$

where e_{input} is the energy (exergy) costs per time unit; τ_p – time for the manufacture of equipment and construction of the plant; τ_l – lifetime of the installation.

The reserved (taken out) energy and exergy can be calculated using the formula:

$$E_{output} = \int_{0}^{\tau_l} e_{output}\, d\tau \,, \tag{4}$$

where e_{output} is the energy (exergy) obtained per time unit; τ_l=0 – the moment of commissioning of the first unit of the plant.

The criterion of efficiency in this method is the coefficient of energy-net, or as it is called coefficient of EROI (Energy Return On Investment), or the coefficient of ExROI (Exergy Return On Investment):

$$EROI = \frac{E_{output}}{E_{prod}} \,, \tag{5}$$

where E_{prod} is the energy consumed for the construction of the facility and creating equipment (not included energy of natural energy resources – fuel, geothermal water, etc., which provides, after conversion, the useful energy received). The higher this coefficient, the more effective is the power plant.

Another important indicator of the method is the term (time) of energy and exergy payback τ_p – is the period of time during which the obtained energy (exergy) compensates the one spent. It can be defined by the equation:

$$\int_{0}^{\tau_p} e_{output}\, d\tau = E_{prod} \,. \tag{6}$$

The project efficiency is higher when the term of its payback is lower.

3. Pilot Plant

The aim of this study was to determine the effectiveness of low-speed wind turbines under different wind intensity conditions from the point of view of a thorough energy net analysis. The layout of WPI-5-4 is shown in Fig. 4, main technical specifications are given in Table 1.

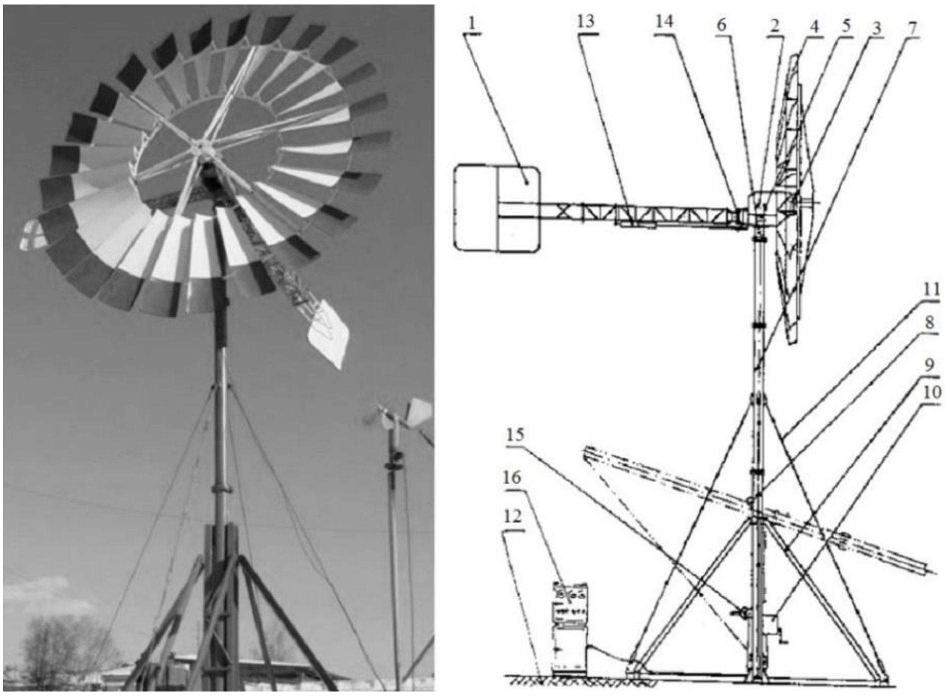

Fig. 4. Layouts and schematic diagrams of the WPI-5-4 wind turbine: 1 – keel; 2 – turntable; 3 – wind wheel; 4 – blades; 5 – side bar with shield; 6 – support unit; 7 – tower; 8 – hinge; 9 – base; 10 – winch; 11 – bracing; 12 – foundation; 13 – stop gear; 14 – hinge; 15 – drive; 16- electric equipment (except mounted in turntable).

Table 1. WPI-5-4 main technical specifications

	Parameter designation	Value
1	Wind driven wheel diameter [m]	5,0
2	Height to the wind wheel axis [m]	8,22
3	Number of blades [pcs]	24
4	The range of operating wind speeds [m/s]	3,5…25
5	Estimated wind speed [m/s]	10
6	Wind wheel running speed [rpm]	55
7	The maximum wind wheel rotation frequency [rpm]	100
8	Wind wheel wind orientation	with the help of the tail beam keel
9	Method of regulation of rotation frequency	taking out from under wind by side bar with a shield
10	Generator rated power [kW]	4
11	Wind turbine weight [kg]	not more than 1500

It is advisable to start energy and exergy analysis of any power plant with a definition of the boundaries of the object being analyzed. Also for all component parts which are included in the object, or are necessary for its operation. The study focused on the low-speed multiple blade vaned wind turbine WPI-5-4 with a horizontal axis of rotation. This wind turbine has a rated power of 4 kW and is designed to operate in areas with a low wind speed for energy supply to certain small less significant consumers.

4. Calculations

Costs of energy and exergy for the production of materials of which the wind turbine is made were estimated by data [6, 13 – 15] for the industry of Russia. In the course of examination of the manufacturer's design documentation considering the existing production technology, energy calculations and exergy costs for the creation of blanks for 217 different parts comprising the wind turbine were made. These parts form 18 sub-assemblies and assemblies, here are the principal ones: bracing, support unit, tower, wind wheel, base, hinge, keel, bar side, holder/support for generator, reduction gear, generator and other related articles, besides in the calculation, the costs for the foundation were taken into account. As a result of the wind turbine design study it was established that a standard range of materials requiring a minimum of machining is used therefore the materials utilization rate is at the level of 0.9. The results of calculation of energy costs for the creation of separate units of WPI-5-4 wind turbine based on the described above methodology are given on Fig. 5. Total energy costs for the creation of the wind turbine calculated according to eq. (2) amounted to 98 653 MJ, exergy costs – 83 699 MJ.

As can be seen from Fig. 5, the most power-consuming element, which accounts for 33% of the energy and exergy cost is the wind wheel. This is due to the fact, that its design mostly utilizes aluminum, which has elevated energy intensity. Power-consuming elements also include the base and the tower, representing 21% and 17% of energy costs and 20% to 18% of exergy costs respectively. This is because these units have the largest weight of all assembly units of the wind turbine.

To determine the coefficient of energy - and exergy-net and, also the time of energy and exergy payback of WPI-5-4 wind turbine, the calculation of its performance was carried out for various conditions of wind capacity using the "Marchenko" method with wind capacity data in different regions of Russia [16]. Wind turbine produce electrical energy, which belongs to the class of "non-entropic", i.e. can be completely transformed into any other kind of energy, so the energy produced is equal to the exergy produced.

In the calculations of EROI and ExROI coefficients for the lifetime of the plant, the manufacturer assigned 10-year period was considered [17], although in many other studies [7-12] this period equals to 15 to 30 years, which significantly affects the overall energy performance for the life cycle and leads to an increase in the values of these coefficients.

The results of the calculations are given in Table 2 and on Figs. 6, 7.

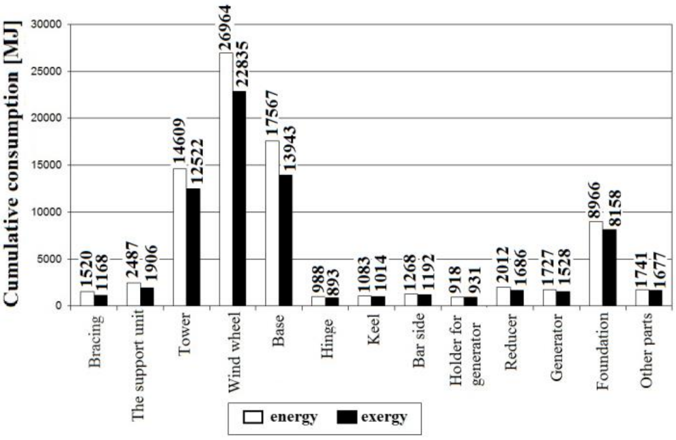

Fig 5. Comparison of the energy and exergy costs for the creation of various elements of the WPI-5-4 wind turbine plant.

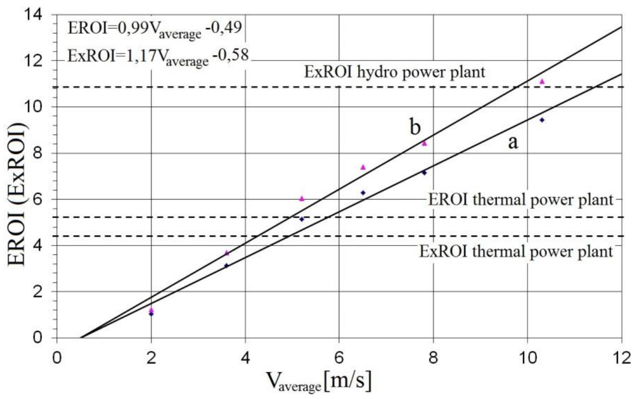

Fig 6. Dependence of coefficient EROI (a), the coefficient ExROI (b) on average wind speed.

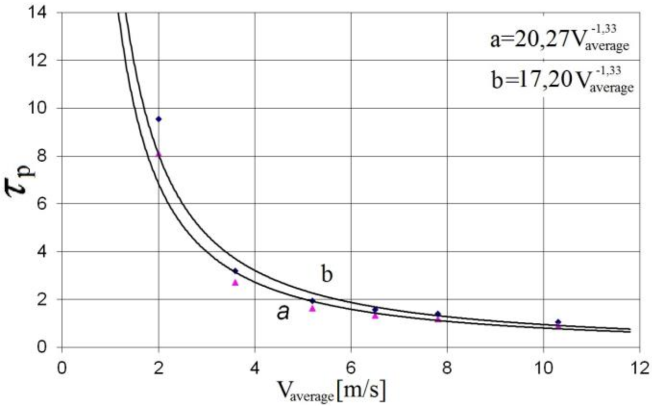

Fig. 7. Dependence of energy payback time (a) and exergy payback time (b) on the average wind speed.

Table 2. The results of calculations of WPI-5-4 energy characteristics:

Parameter	Yaksha	Nizhni Tagil	Ust-Hariuzovo	Anadyr	Ra-Iz	Taganai
Average wind speed [m/s]	2.00	3.60	5.20	6.50	7.80	10.30
Scale parameter *A* of Weibull distribution curve	2.40	4.20	6.00	7.20	8.80	12.00
Shape parameter *k* of Weibull distribution curve	1.47	1.45	1.29	1.60	1.31	1.68
Average power [kW]	0.33	0.98	1.61	1.97	2.24	2.95
Annual energy production, [MJ]	10 328	30 848	50 675	62 037	70 612	93 031
EROI	1.05	3.13	5.14	6.29	7.16	9.43
ExROI	1.23	3.69	6.05	7.41	8.44	11.11
Energy payback time [years]	9.55	3.20	1.95	1.59	1.40	1.06
Exergy payback time [years]	8.10	2.71	1.65	1.35	1.19	0.90

5. Conclusion

Proceeding from the obtained calculation data it is evident that at an average speed of wind of approximately 5 m/s in the considered area, the EROI and ExROI coefficients for a WPI-5-4 wind turbine are at the level of similar indicators for thermal power plant and nuclear power plants [6, 7, 18, 19]. At higher wind speeds, these coefficients increase and begin to exceed the level of similar indicators of traditional energy generation plants reaching an average wind speed of 9.9 m/s, the exergy net coefficient of hydroelectric power plants that provide base loading have the highest value of this coefficient [6]. The data obtained correlates well with indicators of EROI presented in [7, 20] for systems of similar capacity. However, these values are lower than those presented in [8 – 12, 21], since they consider wind turbines with a capacity of several hundred kilowatts, and the value of material consumption per kilowatt of installed capacity in such plants is much lower which causes a higher value of the EROI coefficient [20].

In the manufacturing process of wind turbines thermal energy was used, which refers to the so-called "entropy" group. The wind turbine, in its turn, produces electrical energy, which refers to "non-entropic" group [6]. On this basis, the energy production costs of WPI-5-4 wind turbines exceed the exergy costs and the exergy-net (ExROI) coefficient appears to be higher than the energy-net (EROI) coefficient at the same wind availability.

Terms of energy and exergy payback for the conditions of the considered meteorological stations varied within 1.06 to 9.55 and from 0.9 to 8.10 years, respectively. At an average speed wind in the area of more than 3.6 m/s the power payback time doesn't exceed 3 to 20 years which is a high rate. It is possible to improve the energy characteristics of WPI-5-4 wind turbine, for example, by replacing the material of the wind wheel from aluminum to carbon steel or fiberglass, introducing appropriate changes in the design.

References

[1] C. W. Bullard, P. S. Penner, D. A. Pilati, Net energy analysis: Handbook for combining process and input-output analysis, Urbana: University of Illinois, 1976, pp. 10 – 19.

[2] E. R. Berndt, From technocracy to net energy analysis: engineers, economists and recurring energy theories of value, Oxford: Oxford University Press, 1983, pp. 4 – 36.

[3] C.J. Cleveland, R. Costanza, C.A.S. Hall, R. Kaufmann, “Energy and the U.S. economy: a biophysical perspective”, Science, Vol. 225, pp. 890–897, 1984.

[4] V. S. Stepanov, T.B. Stepanova, Efficiency of use of energy, Novosibirsk: Nauka, 1994. (in Russian)

[5] E. I Yantovski, Energy and exergy flows, Moscow: Nauka, 1988. (in Russian)

[6] V. M. Brodyanski, G. P. Verkhivker, Ya. Ya. Karchev et al. Exergy calculations of technical systems, Kiev: Naukova dumka, 1991. (in Russian)

[7] I. Kubiszewski, C. J. Cleveland, P. K. Endres, "Meta-analysis of net energy return for wind power systems", Renewable Energy, Vol. 35, pp. 218-225, 2010.

[8] D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, A. Hussein, "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants", Renewable Energy, Vol. 52, pp. 210 – 221, 2013.

[9] M. Lenzen, J. Munksgaard, "Energy and CO2 life-cycle analyses of wind turbines - review and applications", Renewable Energy, Vol. 26, pp. 339 – 362, 2002.

[10] B. Guezuraga, R. Zauner, W. Pölz, "Life cycle assessment of two different 2 MW class wind turbines", Renewable Energy, Vol. 37, pp. 37 – 44, 2012.

[11] M. R. Kabir, B. Rooke, G. D. M. Dassanayake, B. A. Fleck, "Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation", Renewable Energy, Vol. 37, pp. 133 – 141, 2012.

[12] B. Tremeac, F. Meunier, "Life cycle analysis of 4.5MW and 250W wind turbines", Renewable and Sustainable Energy Reviews, Vol. 13, pp. 2104–2110, 2009.

[13] V. G. Lisienko, Ya. M. Tshelokov, S. E. Rosin, O.G. Druzhinina, A.E. Parenkov. The energy analysis. The methodology and basic data support, Ekaterinburg: Urals State Technical University- UPI, 2001. (in Russian)

[14] G. A. Isakovich, U. B. Slutskin. Saving fuel and energy resources in construction, Moscow: Stroiizdat, 1988. (in Russian)

[15] G. G. Panchenko, B. P. Korobko, The energy intensity of machine parts blanks, Kiev: NIIIINTI, 1990. (in Russian)

[16] A. N. Starkov, L. Landberg, P. P. Bezrukokh, M. M. Borisenko, Wind atlas of Russia, Moscow: Mozhaisk-Terra, 2000. (in Russian)

[17] GOST P 51991-2002, Alternative power generation. Wind power engineering. Wind power plants. General technical requirements, Russian State Standard, Moscow, 2002. (in Russian)

[18] V. V. Alekseev, Power engineering ecology and economics of energy through the eyes of an ecologist, Moscow: Znanie, 1990. (in Russian)

[19] G. A. Ivanov, N. P. Voloshin, A. S. Ganeev, F. P. Krupin, B. V. Livinov, S. Yu. Kuzminykh, A. I. Svalukhin, L. I. Shabarshov, Explosive deuterium power engineering, Snezhinsk: RFNC – VNIITF, 1996. (in Russian)

[20] J. E. Gates, B. Czech, D. L. Trauger, Peak oil, Economic growth, and wildlife conservation, New York: Springer Science, 2014, pp. 67 – 70.

[21] C. A. S. Hall, J. G. Lambert, S. B. Balogh, "EROI of different fuels and implications for society", Energy policy, Vol. 64, pp. 141 – 152, 2014.