Methodology for determining technical, economic and environmental performance of combined power plants

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Abstract. Consideration of the feasibility of building combined power plants (CPP) based on renewable energy sources (RES) and the choice of parameters, type of equipment, layout, and design solutions is based on an assessment of economic efficiency, the indicator of which is the ratio between the required investments and the achieved technical and economic effect. An accurate assessment of economic efficiency is a rather difficult task since it is necessary to take into account a large number of factors, for example, specific features of design solutions, operating conditions of the CPP depending on the requirements of the consumer, the stochastic nature of the manifestation of energy resources, the possible mode of operation of the CPP for the needs of individual consumers and others. An approach based on the minimum cost criteria has been widely used for the economic justification of the objects under construction for a long time. In rigidly centralized economic management, such an approach based on ensuring optimal construction planning played an important role in increasing the scientific validity of economic decisions. It proceeded from the global and national economic goals of economic development. In the conditions of a free market economy, a method of evaluating the effectiveness of taking into account all the main features of it is necessary.

1 Introduction

All over the world, scientific research is being conducted to improve operating modes and methods aimed at improving the energy, economic, and environmental efficiency of power plants based on renewable energy sources in separate and combined use, aimed at reducing the cost of fuel resources, greenhouse gas emissions, the cost of electricity received and the payback period of power plants [1,2,3]. In this direction, including through the development of effective methods for managing operating modes and technological schemes of combined systems based on renewable energy sources, research is considered a priority to determine the economic feasibility [4,5,6] and assess the reliability, stability,

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and safety [7,8] of electricity generation. This task is reduced to the need to determine and evaluate power plants' technical, economic, and environmental indicators. [9,10,11].

For the correct assessment of the effectiveness of the creation of a CPP, it is of particular importance to take into account the following factors:

1)renewable hydropower resources, manifested in fuel economy and associated costs for fuel extraction, processing, and transportation. The fuel effect on renewable energy installations is a significant part of the overall economic effect, growing yearly [12,13].

2) ecological cleanliness of renewable energy installations. Due to the deterioration of the environmental situation, the requirements governing emissions of harmful substances into the atmosphere during the operation of stations by non-renewable, incinerated sources are being tightened. Ensuring the operation of these stations following these requirements requires huge funds, which negatively affects their economic efficiency [14,15,16].

3) power shortage, frequent disconnections of the centralized power supply network due to energy restrictions. Producers, especially small and medium-sized businesses engaged in agricultural production, incur tens of times more losses than the cost of undelivered energy. Considering this factor when determining the economic effect of renewable energy installations operating in accordance with the schedule of energy consumption of business entities is very important [17,18,19].

Currently, methods for assessing the economic efficiency of various combined power plants have been developed in the economy [1,2,3,4,5]. However, due to the increasing urgency of environmental problems, there is a further development of methods for determining the economic efficiency of combined power plants that consider environmental issues [1].

The object of the experimental study is a silicon polycrystalline photovoltaic module (PVM) of the CHSM66-10P-270W type. Experimental studies of PVM were conducted on the territory of the Tashkent State Technical University (Department of "Hydropower and Hydraulics). The areas of activities of the department are the calculation of improving the efficiency of hydraulic structures [20,21,22], especially pumping stations [3,7,11,23] and hydroelectric power plants [13], as well as power plants based on renewable energy sources [1,3] and especially combined with hydropower plants [9,12]. Currently, one of the main areas of scientific research is the study of the operating modes of power plants based on renewable energy sources and the development of methods for assessing economic efficiency. Therefore, when performing scientific work, two tasks were solved: studying the operation of power plants (their energy and economic parameters) and developing a methodology for evaluating effectiveness.

2 Methods

To analyze the results of measurements of short-circuit current, no-load voltage, the values of short circuit electric current I_{sc} and idling voltage U_{idling} measured at 13-00 hours at the maximum of solar radiation were compared with the nominal values of I_{sc}, U_{idling}, which are indicated on the nameplate of CPP type CHSM66-10P-270W. PVM type CHSM66-10 P-270W was installed at an angle of 45° to the horizon with a southern orientation. The comparison of the measured I_{sc} and U_{idling} with the nominal values of the CPP type CHSM66-10 P-270W is shown in Table 1.

Table 1. Comparison of measured I_{sc} and U_{idling} with nominal values of CPP type CHSM66-10P-270W.

Technical parameters/ Date of measurement	**Nominal values**	**Measured values**	**Deviation**
W, W/m2 / 23.07.2022	1000	918	-82
W, W/m2 / 23.08.2022	1000	928	-72
I_{sc}, A /23.07.2022	9.45	7.86	-1.59
I_{sc}, A /23.08.2022	9.45	8.81	-0.64
U_{idling}, V / 23.07.2022	38.0	29.5	-8.5
U_{idling}, V / 23.08.2022	38.0	30.6	-7.4

Field studies and tests to determine the energy-hydraulic parameters of micro-electric power plants were carried out at the source - the Turnabulak River (Uzbekistan) [13].

The results of measurements of micro-electric power plants with a propeller turbine are shown in the graph in Fig. 1.

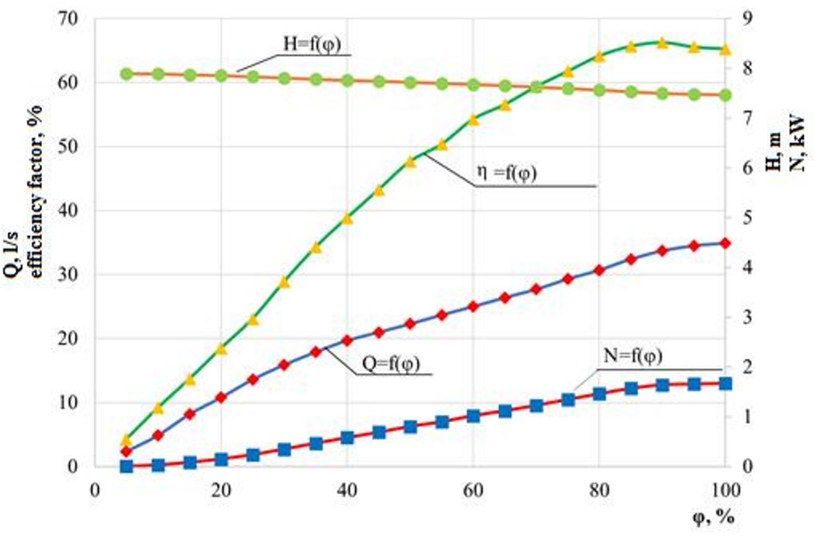
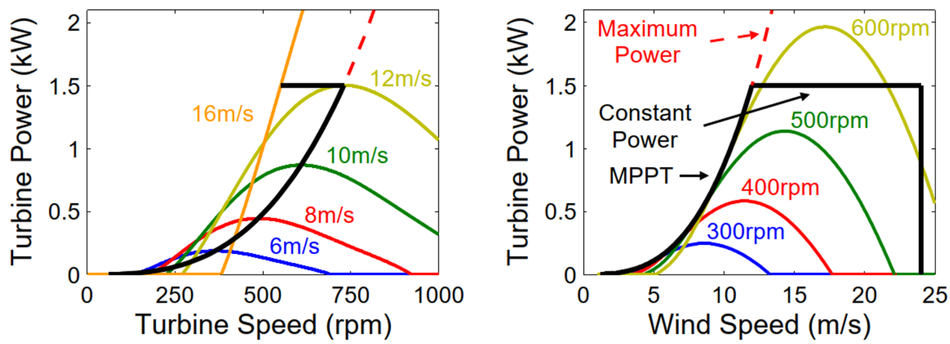


Fig. 1. Results of field tests of micro-electric power plants with propeller turbine

It is believed that the operating wind speeds for wind turbines should be about 8-10 m/s [24,25,26]. However, recently there has been a problem with using wind turbines in regions with lower wind speeds. In this regard, the task of determining the technical and economic characteristics of wind turbines in such regions seems urgent [1].

In this paper, based on the analysis of wind turbine characteristics, approximation dependencies for wind turbine parameters of different power are proposed in Fig. 2. The paper considers combined installations based on renewable energy sources without taking into account changes in the technical and economic characteristics of wind turbines when the design (operating) speeds change, i.e., the possibility of using wind turbines in regions with wind speeds lower than the commonly used design speeds at the level of 8-10 m/s, i.e., when designing wind turbines, the nominal wind speed V_n in this region and the design of wind speed V_d should be set (for three-bladed wind turbines, it is currently considered that V_d is of the order of 8-10 m/s) [25].



(a) Turbine speed (b) Wind speed

Fig. 2. Graph of dependence of power of low-power wind turbine on wind speed V and total shaft speed n

The following technical and economic indicators were used in the analysis and development of the methodology for calculating the efficiency of installations CPP [12,19,27,28,29]:

- capital investments in the CPP K_{CPP};
- electricity generation for the consumer $E_{consumer}$;
– accumulating electricity in rechargeable battery (accumulator battery- AB) E_{AB};
– annual saving of fuel resources for fuel D_{fuel};
– economy is fuel E_{fuel};
– annual cost of operational costs OC_{CPP};
– reduction of annual emissions of CO_2 ΔEM;
– economic efficiency for the year EFF_{CPP};
– payback period of capital investments $T_{payback}$;
– profitability of capital investments R.

As you know, economic efficiency generally represents the difference between income and costs. Let's consider the economic characteristics of the CPP, taking into account the above-mentioned features of its application. Investments in the CPP K_{CPP} are generally equal to [27,28]:

$$K_{CPP} = N_W \cdot C_{WPP} + N_H \cdot C_{HPP} + N_{AK} \cdot C_{AK} + N_S \cdot C_{SPP}, [\$] \quad (1)$$

Where
N_S , N_W , N_H are the power of solar, wind, and hydropower plants. \$/kW
C_{SPP}, C_{WPP}, C_{HPP} are the total unit cost of solar, wind, and hydropower plants. \$/kW
Electricity generated by the CPP *Egen*:

$$E_{gen} = E_{cons} + E_{AK}, [kWh] \quad (2)$$

Annual electricity generation for the consumer $E_{consumers}$:

$$E_{consumer} = E_{fullday} \cdot t_{days}, [kWh] \quad (3)$$

where t_{days} are the days of work during the year (330 days can be accepted for the conditions of Uzbekistan); $E_{fullday}$ is the generation of electricity during the day for the consumer [1,3].

Annual accumulated electricity in AB E_{AK} [3,6]:

$$E_{AK} = N_{AC} \cdot t_{AC}, \cdot t_{days}, [kWh] \quad (4)$$

where t_{AC} is the time of accumulation of electricity in AB during the day; t_{days} is the days of operation during the year N_{AC} is the battery capacity, determined by the following:

$$N_{AC} = \frac{W_{bat}^{total} U_{in} \gamma}{24 n_{out} K} [kW] \quad (5)$$

where n_{out} is the number of days during which the PVM cannot work (due to weather conditions or for another reason);

U_{in} is incoming voltage, V;

K is a coefficient that considers the ambient temperature in the room where the AB is installed.

K = 1.11 at a temperature of 15.6^0 C.

K = 1.19 at a temperature of 10.0^0 C.

K = 1.30 at a temperature of 4.4^0 C.

γ is the value of the permissible discharge of the battery, which can be assumed to be 0.2 - 0.3 since large discharge values degrade the battery's performance.

W_{bat}^{total} is the total capacity of the batteries. It is determined by the following dependence:

$$W_{bat}^{total} = \frac{A_{hour} n_{out} K}{\gamma} [kW*h] \quad (6)$$

where A_{hour} is the daily requirement in *ampere•hours*:

$$A_{hour} = \frac{E}{U_{in}} [A*h] \quad (7)$$

Annual saving of fuel resources of fuels D_{fuel} [27,28,30]:

$$D_{fuel} = \gamma_{fuel} * E_{consumer}, \text{[kg of standard fuel]} \quad (8)$$

where γ_{fuel} is the specific fuel economy per 1 kWh of electricity, kg.s.f./ kWh.

Fuel economy:

$$E_{fuel} = D_{fuel} * \beta_{fuel}, [\$] \quad (9)$$

where β_{fuel} is the cost of 1 kg.s.f, [$/kg.s.f].

Annual operational costs OC_{CPP} are determined by the formula:

$$OC_{CPP} = C_{amortization} + C_{repair} + C_{salaries} + C_{other}, [\$] \quad (10)$$

where $C_{amortization}$ is the amortization cost for the CPP, we accept 5% of the capital investments K_{CPP} for the creation of the CPP:

$$C_{amortization} = 0.05\ K_{CPP},\ [\$]. \tag{11}$$

C_{repair} is repair maintenance costs, 18% of the $C_{amortization}$ is accepted:

$$C_{repair} = 0.18\ \ C_{amortization} = 0.18 \cdot 0.05\ K_{CPP} = 0.009\ K_{CPP},\ \ [\$] \tag{12}$$

$C_{salaries}$ is salaries of service personnel,
C_{other} is other expenses (overhead).

$$C_{other} = 0.15(C_{amortization} + C_{repair} + C_{repair}) = 0.15\ (0.059K_{CPP} + C_{salaries}),\ \ [\$]. \tag{13}$$

For CPP with a capacity of more than 100 kW:

$$C_{CPP} = 0.06785K_{CPP} + 1.15\ C_{salaries},\ [\$] \tag{14}$$

For CPP with a power of less than 100 kW (C_{other} = 0; $C_{salaries}$ = 0):

$$C_{CPP} = 0.05\ K_{CPP} + 0.009\ K_{CPP} = 0.059\ K_{CPP},\ [\$] \tag{15}$$

The cost of the energy produced (prime cost) by the above installations is determined by the following dependence:

$$C_{prime} = C_{CPP} / E_{consumer}, \tag{16}$$

The cost of electricity generated for consumption by the CPP:

$$P_{CPP} = E_{consumer} \cdot \beta_{EP},\ [\$] \tag{17}$$

β_{ep} – electricity tariff, *\$/(kW•hour).*
And the annual economic efficiency of the CPP will be equal to:

$$EFF_{CPP} = P_{CPP} + E_{fuel} + \Delta EM - C_{CPP} - 0.15\ K_{CPP},\ [\$] \tag{18}$$

where ΔEM is the effects of reducing greenhouse gas emissions.
The effect of reducing greenhouse gas emissions due to the CPP is determined by the expression:

$$\Delta EM = EM \cdot \beta_{CO2}\ [\$], \tag{19}$$

where
β_{CO2} is the annual cost of environmental measures to clean up from CO^2 taken 15...20 \$/ton;
EM is the annual CO^2 emission (tons/year) for each type of fuel (combustion plants) produced according to the formula:

$$EM = M * K_1 * CV_{fuel} * K_2 \bullet 44/12, \tag{20}$$

where M is the actual fuel consumption for the year:

$$M=\gamma_{fuel} * E_{consumer}, \quad [ton/year] \qquad (21)$$

γ_{fuel} is the specific fuel consumption per 1 kWh of electricity.

K_1 is the coefficient of carbon oxidation in fuel (shows the proportion of burnt carbon), K_1 = 0.98-0.995 (for coal – 0.98, for oil and petroleum products – 0.99, for gas – 0.995); CV_{fuel} is the net calorific value (J/tons) (for petroleum fuel is 41.15 GJ/tons, for coal is 17.62 GJ/tons, for natural gas is 34.78 GJ/tons);

K_2 is the coefficient of carbon emissions (tons/J) (for petroleum fuel - 20.84 t/TJ, for coal - 25.58 t/TJ, for natural gas - 15.04 t/TJ);

44/12 is the coefficient of conversion of carbon into carbon dioxide (molecular weights, respectively: carbon - 12 g/mol, O_2 = 32 g/mol, CO_2 = 44 g/mol).

The formulas obtained are general; however, there are features when assessing the economic effects for a CPP with a capacity of less than 100 kW. So, for example, the component of $0.15K_{CPP}$ is not taken into account (other expenses – infrastructure costs, ecology, etc.) (14 and 15).

The payback period $T_{payback}$ and the profitability R of capital investments in the CPP were determined by well-known formulas [27,28].

3 Results and discussions

If there are many methods for determining the economic efficiency of power plants operating separately [31,32,33], then there are few methods for combined power plants working together. Combined solar and wind power plant systems are mainly considered [34,35,36]. In addition, when developing methods, it is necessary first to consider local peculiarities (economic, social, and environmental) [2,35,36,37]. The proposed methodology for calculating the economic efficiency of combined power plants (solar, wind, and hydraulic) considers all economic, natural, and socio-ecological features of the Republic of Uzbekistan.

Based on the above methodology, calculations were carried out to determine the technical, economic, and environmental indicators of a 100 kW power plant. Based on the approximation of the results, a diagram was constructed (Fig.2) to determine the payback period of a 100 kW power plant with different power ratios of three types of renewable energy plants (solar power plant SPP, wind power plant WPP and hydropower plant HPP).

As a result of the calculations carried out, the following technical and economic indicators were determined for the CPP based on the SPP, wind turbine, and HPP with a capacity of 100 kW:

- fuel resource savings – 64.68 t.s.f.;

– cash income from the saved fuel –17 570 $;

– reduction of annual CO2 emissions – 682 tons/year;

– environmental efficiency –13 640 $ /year;

– the economic efficiency of the CPP, depending on the combination of the power of the SPP, wind turbine, and CPP – 32000÷40000 $ / year.

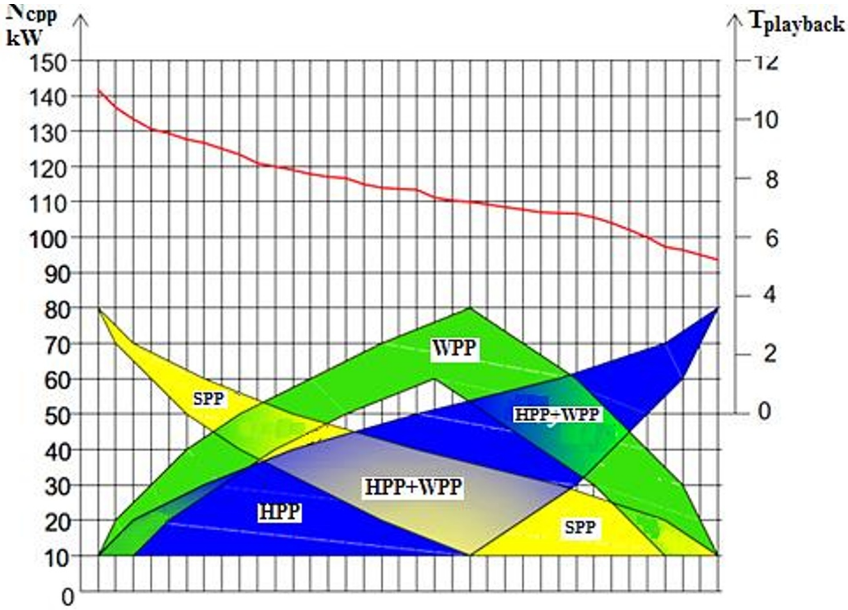


Fig. 1. Diagram for determining the payback period of CPP with capacity of 100 kW at different power ratios of three types of renewable energy installations.

4 Conclusions

1. A methodology has been developed for calculating the economic efficiency of combined power plants based on renewable energy sources, which considers all economic, natural, and socio-ecological features of the Republic of Uzbekistan.

2. According to this methodology, the technical and economic indicators of a 100 kW CPP were determined, and a diagram was constructed to determine the payback period for different power ratios of three types of renewable energy plants (SPP, WPP, HPP). As can be seen, the cost of power for a consumer with an SPP significantly exceeds the cost of the power of an SPP for the manufacturer. Of course, as in the case of wind turbines (WPP), with an increase in load capacity, or thus, with an increase in the power of the power plant, the cost of power will fall. It can also be seen that with low water consumption, as in wind turbines of WPP, the power costs of HPP are the highest.

3. The developed methodology for determining economic efficiency and the diagram can be used in designing, calculating, and selecting equipment for combined power plants based on renewable energy sources in Uzbekistan.

References

1. M. Mukhammadiev, B. Urishev, A. Abduaziz uulu, O. Almardanov, N. Karimova, H. Murodov, The role of renewable energy sources in providing the efficiency of the power system in the conditions of digital energy transformation, in AIP Conference Proceedings 2552, 050019 (2023); https://doi.org/10.1063/5.0111764, (2023)
2. M.Kaltschmitt, W. Streicher, A.Wiese, Renewable energy : technology, economics and environment (Springer-Verlag Berlin Heidelberg, 2007)
3. M. Mukhammadiev, K. Dzhuraev, S. Juraev, N. Karimova, A. Abduaziz uulu, A.Makhmudov. Methodology for substantiation of technical and economic indicators

of PSPP in energy water management systems of Uzbekistan. In E3S Web of Conferences 264, 04056 (2021). doi.org/10.1051/e3sconf/202126404056

4. K.Wang, M.Herrando, A. Pantaleo, C.Markides, Techno-economic assessments of hybrid photovoltaic-thermal vs. conventional solar-energy systems: Case studies in heat and power provision to sports centres, Applied Energy, 254, 113657 (2019)
5. L.Qi, M. Jiang, Yu.Li, Z. Zhang, J.Yan, Techno-economic assessment of photovoltaic power generation mounted on cooling towers, Energy Conversion and Management, 235, 113907 (2021)
6. J. Menendez, J.Loredo, Economic feasibility of developing large scale solar photovoltaic power plants in Spain, in E3S Web of Conferences 122,02004 (2019)
7. N.Ikramov, T.Majidov,E. Kan, A Mukhammadjonov, Monitoring system for electricity consumption at pumping stations, in CONMECHYDRO-2020, IOP Conf. Series: Materials Science and Engineering, 883 012101 doi:10.1088/1757-899X/1/012101 (2020)
8. Burlachenko A., Chernykh O., Khanov N., Bazarov D. Features of operation and hydraulic calculations. E3S Web of Conferences, 2023, 365, 03048.
9. I. Yahyaoui, Advances in Renewable energies and power technologies (Elsevier, 2018)
10. M.M. Mukhammadiev, K.S Dzhuraev. Justification of the energy and economic parameters of pumped storage power plants in Uzbekistan. International journal "Applied Solar Energy", Vol. 56, №3, pp.227-232.(2020)
11. E. Kan, M. Mukhammadiev, A. Li, Sh. Aralov, Methodology for assessing the efficiency of water jet pumps in auxiliary systems of irrigation pumping stations. In E3S Web of Conferences 304,01003, DOI 10.1051/e3sconf/202130401003 (2021)
12. I. Yahyaoui, Advances in Renewable energies and power technologies (Elsevier, 2018)
13. M.Mukhammadiyev, B. Urishev, E. Kan, K. Juraev, New methods of application of micro-hydroelectric power plants at existing hydraulic structures: Schemes, parameters, efficiency, in E3S Web of Conferences, 320, 04009, (2021)
14. A.Heshmati, Energy economics and policy in developed countries (MDPI, Basel, Switzerland,2020)
15. S. Khushiev, O. Ishnazarov, S. Juraev, J. Izzatillaev, A. Karakulov, Construction of an electric drive system for borehole pumps with frequency control, in Proceedings of the 2nd International Conference on Energetics, Civil and Agricultural Engineering, ICECAE 2021, 14 - 16 October 2021, AIP Conference Proceedings, 2686, 020018, DOI:10.1063/5.0114016 (2022)
16. Z.Malikov, D. Navruzov, K. Adilov, S. Juraev, Numerical study of a circular jet based on a modern turbulence model, in Proceedings of Computer Applications for Management and Sustainable Development of Production and Industry, CMSD 2021, Dushanbe, 21- 23 December 2021, Proceedings of SPIE - The International Society for Optical Engineering,122512022,122510H, DOI 10.1117/12.2631607(2022)
17. D. Yogi Goswami, F. Kreith, Energy efficiency and renewable energy (CRC Press, Taylor and Francis Group, 2016)
18. B.Turkay, A. Telli, Economic analysis of stand alone and grid connected hybrid energy systems, Renewable Energy, 36 (7), 1931-1943 (2011)
19. S. Bhattacharyya, Energy economics. Concepts, issues, markets and governance (Springer-Verlag London Limited, 2011)

20. Bazarov, D. R., Norkulov, B. E., Kurbanov, A. I., Jamolov, F. N., & Jumabayeva, G. U. Improving methods of increasing reliability without dam water intake. In AIP Conference Proceedings. Vol. 2612, No. 1. AIP Publishing. (2023).
21. Bazarov, D., Krutov, A., Sahakian, A., Vokhidov, O., Raimov, K., & Raimova, I. Numerical models to forecast water quality. In AIP Conference Proceedings, Vol. 2612, No. 1, p. 020001. AIP Publishing LLC. (2023)
22. Mamajanov, M., Uralov, B. R., Artikbekova, F. K., Vokhidov, O. F., Nazarov, B. U., & Rayimova, I. Influence of cavitation-hydro abrasive wear and wear of vane hydraulic machines on the hydraulic resistance of the suction line of pumping units. In AIP Conference Proceedings, Vol. 2612, No. 1. AIP Publishing. (2023)
23. B.Uralov, S. Berdiev, M. Rakhmatov, O. Vokhidov, L.Maksudova, I. Raimova, Theoretical models and dependences for calculating intensity of hydroabrasive wear of pump working parts, in E3S Web of Conferences, 365, 03019, https://doi.org/10.1051/e3sconf/202336503019 , (2023)
24. O.Marchenko, S. Solomin, The investigation of economic efficiency of wind turbines in dezentralized energy systems, Int. Sc. J. for Alternative energy and Ecology, 8 (81), 126-131 (2010)
25. J.Martin, The economics of Wind energy, J. of Applied Corporate Finance, 21(2), (2009)
26. Y.Charabi, S. Abdul-Wahab, Wind turbine performance analysis for energy cost minimization, Renewables: Wind, Water, and Solar, 7:5, doi.org/10.1186/s40807-020-00062-7 (2020)
27. F.Forsund, Hydropower Economics (Springer, New York, 2015)
28. D.Shchavelev, M.Gubin, V.Kuperman, M.Fedorov, Economics of hydraulic engineering and water management construction (Stroyizdat, Moscow, 1986)
29. A.Razmjoo, M. Qolipour, Technical-economic evaluation of solar energy potential for the city of Ahvaz, Int. J. of renewable energy technology research, 5 (1), 1-10, (2016)
30. O.Marchenko, S. Solomin, Economic efficiency assessment of autonomous wind/diesel/hydrogen systems in Russia, J. of Renewable energy, 2013, 101972 (2013)
31. J.Servert, G.San-Miguel, D.Lopez, Hybrid solar-biomass plants for power generation: technical and economic assessment, Global NEST J., 13(3), 266-276 (2011)
32. O.Marchenko, S. Solomin, The investigation of economic efficiency of wind turbines in dezentralized energy systems, Int. Sc. J. for Alternative energy and Ecology, 8 (81), 126-131 (2010)
33. Y.Charabi, S. Abdul-Wahab, Wind turbine performance analysis for energy cost minimization, Renewables: Wind, Water, and Solar, 7:5, doi.org/10.1186/s40807-020-00062-7 (2020)
34. N.Jha, D.Prashar,M.Rashid, Z.Khanam, A.Nagpal, A.AlGhamdi,S.Alshamrani, Energy-Efficient Hybrid Power System Model Based on Solar and Wind Energy for Integrated Grids, J.Mathematical problems in engineering, Computational Intelligence and Renewable Energies,Vol. 2022, (2022).
35. G. Notton, "Hybrid wind-photovoltaic energy systems," in Stand-Alone and Hybrid Wind Energy Systems, Woodhead Publishing, Sawston, UK, (2010).
36. C. Mata Yandiola, Feasibility Analysis of the Use of Hybrid Solar PV-Wind Power Systems for Grid Integrated Mini-Grids in India, Dissertation, KTH, School of Industrial Engineering and Management (ITM). Selco Foundation, Stockholm, Sweden, (2017).