UDC 621.311.243(476)

ESTIMATION OF OPERATIONAL EFFICIENCY OF FIXED AND SOLAR TRACKING PV SYSTEMS IN BELARUS CLIMATE

A. P. Meshyk[1], K. A. Meshyk[2], M. V. Barushka[3], V. A. Marozava[4]

[1] Ph.D in Engineering, Associate Professor, Head of the Department of Environmental Engineering, Brest State Technical University, Brest, Belarus, e-mail: omeshyk@gmail.com
[2] Master of Engineering Science, Teaching Assistant at the Department of Heat and Gas Supply and Ventilation of Brest State Technical University, Brest, Belarus, e-mail: krill3april@mail.ru
[3] Master of Engineering Science, Senior Lecturer of the Department of Foreign Languages, Brest State Technical University, Brest, Belarus, e-mail: borushko.marina@mail.ru
[4] Master of Engineering Science, Senior Lecturer of the Department of Descriptive Geometry and Engineering Graphics, Brest State Technical University, Brest, Belarus, e-mail: vmorozova-brest@mail.ru

Abstract

The authors of the article estimate a feasibility of utilizing solar power facilities on the territory of Belarus. They calculate total values of solar radiation under ideal weather conditions and make conclusions about operational efficiency of fixed and tracking PV systems.

Keywords: Solar power facilities, PV system, installed capacity, Belarus, total solar radiation, fixed PV collector, single-axis tracker, two-axis tracker.

ОЦЕНКА ЭФФЕКТИВНОСТИ РАБОТЫ СТАЦИОНАРНЫХ И РЕГУЛИРУЕМЫХ ГЕЛИОСИСТЕМ В КЛИМАТИЧЕСКИХ УСЛОВИЯХ БЕЛАРУСИ

О. П. Мешик, К. О. Мешик, М. В. Борушко, В. А. Морозова

Реферат

В работе оценивается целесообразность применения гелиосистем для территории Беларуси. Установлены суммарные значения поступлений солнечного излучения в идеальных климатических условиях при стационарном размещении гелиоустановки, а также с динамическим стремлением к ортогональному закреплению воспринимающей поверхности по отношению к центру солнечного диска на базе одноосевого и двухосевого регулирования. Сделаны выводы о роли географического положения эксплуатируемых гелиосистем.

Ключевые слова: гелиосистемы, установленная мощность, Беларусь, солнечное излучение, стационарное расположение, одноосевое регулирование, двухосевое регулирование.

Introduction

A transfer from traditional sources of energy to renewable ones is quite reasonable due to the stable population growth and increasing consumption of energy. Alternative power resources are becoming more and more popular since they are inexhaustible, reduce our use of non-renewable potential of nature, and eliminate environmental damage caused by mining works and CO_2 emissions.

In Belarus solar industry seems the most promising kind of alternative energy among others. It is confirmed by the experience and implementation of the technology in neighboring countries with the climate features similar to Belarusian [1]. In accordance with the global distribution of solar radiation in different regions of the world the territory of our country receives 2655 kWh/m^2 of solar energy in the atmospheric boundary layer and 1184 kWh/m^2 on the underlying terrain, which actually correspond to the figures in Germany (2764 kWh/m^2, 1137 kWh/m^2, respectively) and Great Britain (2655 kWh/m^2, 1015 kWh/m^2, respectively). If we also take into account lower air temperatures in Belarus, we might assume even higher performance of solar power facilities here [2].

From 2000 till 2019 the total capacity of solar power plants increased 479 times and reached 587,134 MW [3]. Today, 108 solar plants in use generate electricity from solar radiation in Belarus. Their installed power capacity is increasing annually. In 2020 it reached 159 MW [4].

Some research that estimates the climate potential for developing solar industry in Belarus reveals that the potential here is 10% higher than in Poland or the Netherlands and it is 17% higher than in Germany, Belgium, Denmark, Ireland or Britain. Consequently, the climate factor cannot be regarded as a constraining one [1, 5, 6, 7, 8, etc.]. What can really restrict solar industry here is the cost efficiency of current solar panels available on the market and low electricity tariffs that do not allow the owners to return on their investment fast enough. Although, it is worth taking into consideration that the efficiency can be improved by implementing automated orientation of solar panels to the sun. It can be achieved with the use of an adjustment technology with single-axis and two-axis trackers [9].

Methods and Materials

This research uses meteorological data provided by Belhydromet (Republican center for hydrometeorology, control of radioactive contamination and environmental monitoring) in 2020-2021. These include hourly temperature fluctuations and wind regime in the area under study [10]. The universal assessment criterion is total solar radiation received in ideal clear sky weather. The authors of this research applied such methods of statistical processing of experimental data as regression analysis, time series analysis, spatial generalization of meteorological data, etc. Calculation was automated with the use of SunCalc and MS Excel applications.

Results and Discussion

Total solar radiation incident on an inclined surface is the sum of three components: beam, diffuse, and reflected radiation.

In general, this sum of solar radiation can be calculated with the following formula [11]

$$Q = S_{nakl} + D_{nakl} + R_{nakl}\ , \tag{1}$$

where S_{nakl} is the beam solar radiation incident on a tilted surface of a PV panel, W/m^2; D_{nakl} is the diffuse solar radiation incident on a tilted surface of a PV panel, W/m^2; R_{nakl} is the solar radiation reflected from underlying terrain and incident on a tilted surface of a PV panel, W/m^2.

The amount of beam radiation incident on an inclined surface depends on the amount of radiation reaching the surface orthogonal to the sun and the cosine of an incidence angle which changes during the day [12]

$$S_{nakl} = S_{ort} \cdot cos\theta, \tag{2}$$

where S_{ort} is the beam solar radiation incident on an orthogonal surface, W/m^2; θ is the angle of incidence of S_{nakl} on a PV collector, rad.

The amount of beam radiation incident on an orthogonally oriented surface is calculated here according to the adapted formula by Kastrov [2]

$$S_{ort} = S_0 - \frac{S_0 \cdot c}{c + sin\alpha}, \quad (3)$$

where S_0 is the solar radiation in the top atmosphere, W/m^2; α is the sun elevation angle, rad; c is the air transparency index.

The angle of sun rays incidence on a tilted surface θ allows us to assess the amount of beam radiation at a certain time. In order to calculate it foreign researchers use data about the sun declination angle around polar axis γ displaced from the south [13, 14, 15]. This angle represents the PV panel's azimuth declination. We apply the algorithmic approach to calculate the optimal orientation of a PV panel. That is why angle γ is displaced from the north as the sun's azimuth

$$cos\theta = sin\delta \cdot sin\varphi \cdot cos\beta + sin\delta \cdot cos\varphi \cdot sin\beta \cdot cos\gamma + \\ + cos\delta \cdot cos\varphi \cdot cos\beta \cdot cos\omega - cos\delta \cdot sin\varphi \cdot sin\beta \cdot cos\gamma \cdot cos\omega - \\ - cos\delta \cdot sin\beta \cdot sin\gamma \cdot sin\omega, \quad (4)$$

where δ is the geocentric declination, rad; φ is the latitude of location, rad; β is the incidence angle of a PV collector to the underlying surface, rad; γ is the sun's azimuth, rad; ω is the hour angle, rad.

We choose Brest and Vitebsk as geographic points to locate our PV systems as there is a big demand for electricity in the regions and to avoid losses of electricity during its transmission to large distances.

A PV panel is located effectively if its collector is mounted orthogonally to the sun at noon so as to receive the biggest possible share of direct beam radiation during the day. The angle directly depends on the panel's location and spatial characteristics of the sun at the point. We propose to make the adjustment of the PV system all the year round horizontally and both horizontally and vertically. It will allow us to assign the incidence angle of the PV system β as equal to the latitude of the location φ. In the case of single-axis trackers it is preferable to adjust the system daily β [14] when geocentric declination is as a correction factor,

$$\beta^n_{sut} = |\varphi - \delta|, \quad (5)$$

However, in the case of two-axis trackers it is not necessary to determine the incidence angle of the PV system as the beam radiation reaches the underlying surface orthogonally ($cos\theta = 1$).

The diffuse radiation incident on a titled surface is calculated with the following equation [16]

$$D_{nakl} = D_{gor} \cdot (0{,}55 + 0{,}434 \cdot cos\theta + 0{,}313 \cdot cos^2\theta), \quad (6)$$

where D_{gor} is the diffuse radiation incident on a horizontal surface, W/m^2.

In order to estimate the reflected radiation most experts apply the isotropic model [17]

$$R_{nakl} = Q_{gor} \cdot A_k \cdot (1 - cos\beta) \cdot 0{,}5, \quad (7)$$

where Q_{gor} is the total solar radiation incident on a horizontal surface, W/m^2; A_k is the albedo of the ground surface.

As a result, we estimated the intensity of total solar radiation incident on the surface of the PV collector randomly oriented in space. The calculation method was applied for solar power facilities with fixed orientation as well as for single-axis and two-axis trackers.

The maximum output capacity was calculated with the formula [18]

$$P_{sp} = K_w \cdot N_{sp} \cdot \eta_s \cdot Q \cdot ln\, 10^6 \cdot Q / T_{sp}, \quad (8)$$

where K_w is the coefficient of the solar panel CVC; N_{sp} is the number of solar panels ($N_{sp} \neq 1$ if medium-scale and large-scale trackers are used), items; η_s is the performance coefficient of the solar panel; Q is the total solar radiation, W/m^2; T_{sp} is the current temperature of the panel, °C.

We determined the total solar radiation in the following time periods:

1. January 2020-2021 (hourly determined radiation);
2. July 2020-2021(hourly determined radiation);
3. June 22nd, 2020 (minutely determined radiation).

The data about local air temperature and wind velocity necessary to determine a temperature regime of the PV panels were obtained from weather monitoring databases [10]. In order to facilitate calculation the values were averaged to hourly units. Actual duration of sunshine that changes every day was determined with SunCalc application.

We determined hourly peaks of all the radiation types from sunrise to sunset for each of the time periods under question. In order to optimize the results received we can provide aggregate number of the peaks for each day which are determined as follows

$$Q^n_m = Q^1_m + Q^2_m + \ldots + Q^{31}_m, \quad (9)$$

where Q^n_m is the total solar radiation obtained from the hourly determined peaks, kW/m^2; n is the number of the day; m is the number of the month.

For example, on January 1st, 2020 the duration of daylight in Brest was 7 hours 48 minutes. The sun rose at 9.35 a.m. and set at 5.23 p.m. The sun was at its zenith at 1.29 p.m. It is the time of maximum possible peak capacity in hourly units. As there is very little sunshine during the first few minutes after the sunrise and a few minutes before the sunset, we can ignore them. Therefore, we calculated the data from 10 a.m. to 5 p.m. This approach was used to calculate the total solar radiation in January and July 2020 and 2021 in Brest and Vitebsk. The calculation results are given in Table 1.

Table 1 – Total solar radiation per month

Month, year	Total solar radiation, kW/m^2					
	Fixed PV collector		PV with 1-axis tracker		PV with 2-axis tracker	
	Brest	Vitebsk	Brest	Vitebsk	Brest	Vitebsk
January 2020	64.45	48.37	111.88	87.13	127.74	104.70
January 2021	65.30	49.16	112.86	88.11	128.82	105.83
July 2020	348.19	333.65	401.97	400.81	428.47	432.68
July 2021	349.07	334.59	402.06	400.95	428.53	432.79

It is evident from the table that PV systems with two-axis tracker work much more efficiently than either fixed or single-axis ones. In winter two-axis trackers receive 1.14-1.2 times as much radiation as one-axis trackers and 1.97-2.17 times as much as the fixed ones depending on their geographic location. In summer, two-axis trackers receive 1.07-1.08 times as much radiation as one-axis trackers and 1.23-1.3 times as much as the fixed ones.

Under ideal weather conditions deviation in the calculation results in 2020 and 2021 is insignificant. It allows considering anticipated output capacity in advance. Maximum output capacity of the three PV collectors in the mentioned time periods are calculated with formula (8). The calculation results of the total output of the PV systems in Brest and Vitebsk are given in Table 2.

Table 2 – Total output capacity of PV collectors per month

Month, year	Total solar radiation, kW/m^2					
	Fixed PV collector		PV with 1-axis tracker		PV with 2-axis tracker	
	Brest	Vitebsk	Brest	Vitebsk	Brest	Vitebsk
January 2020	7.13	5.09	15.30	11.15	18.18	14.17
January 2021	7.24	5.19	15.47	11.31	18.37	14.36
July 2020	33.07	30.81	38.92	38.29	42.96	43.06
July 2021	33.16	30.91	38.92	38.29	42.96	43.06

The characteristic features of the solar radiation received appear to be different in these types of PV systems. To show the difference more vividly we calculated the radiation in minute units and separated it into beam radiation incident on a tilted surface S_{nakl}, and the sum of diffuse and reflected radiation $D_{nakl} + R_{nakl}$. We also took into account the maximum capacity of converter P_{sp}. The longest day of the year, June 22nd, 2020 was taken as an example of calculation. In our calculation we used actual duration of daylight. The summed up values are presented in Table 3.

Figures 1–3 show the parameters changing per minute if either a fixed PV panel or a single-axis tracker or a two-axis tracker is employed.

doi.org/10.36773/1818-1112-2021-126-3-85-87

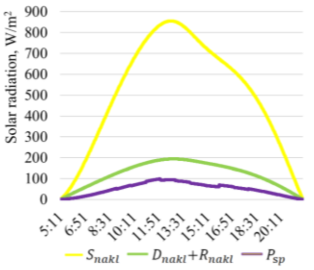

Figure 1 – Dynamic in solar radiation coming per minute and maximum capacity of a fixed PV system

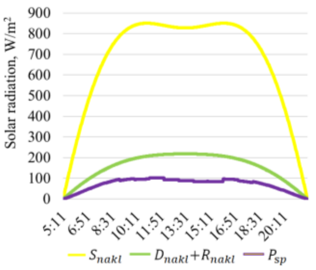

Figure 2 – Dynamic in solar radiation coming per minute and maximum capacity of a single-axis tracker

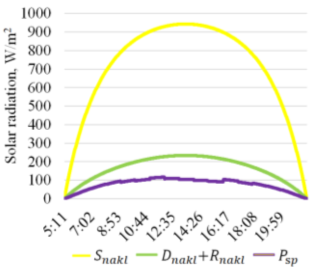

Figure 3 – Dynamic in solar radiation coming per minute and maximum capacity of a two-axis tracker

Table 3 – Summed up values per minute on June 22nd, 2020

Adjustment of PV system	S_{nakl}, W/m²	D_{nakl} + R_{nakl}, W/m²	P_{sp}, W/m²
Fixed PV collector	506.81	121.56	50.71
Single-axis tracker	664.56	155.46	71.18
Two-axis tracker	706.36	161.06	77.15

Conclusion

Climate conditions in Belarus are quite suitable to develop solar industry. The figures calculated in the research show an insignificant deviation although Brest and Vitebsk are situated quite far from each other. The deviation is more typical of summer. In winter the energy yield is better in Brest. But the total net generation reduces significantly as the angle of the sun elevation changes and the daylight shortens. The results obtained in the research confirm a sufficient power potential. However, in real life conditions it is necessary to take into account clouds as an important factor that can affect the energy generation. This factor is to be investigated in our further research where we are going to analyze cloudiness and use an algorithmic approach to operate PV systems according to the weather forecast [19].

This comparative analysis reveals that the PV systems with two-axis trackers are the most productive type of the three. They capture solar radiation 34.27% more effectively than the fixed PV systems and 7.73% more effectively than single-axis trackers.

References

1. Meshyk, O. P. Assessment of solar energy resources of the climate of Belarus / O. P. Meshyk, M. V. Borushko, V. A. Morozova // Bulletin of Brest State Technical University. Water management construction, heat power engineering and geoecology. – 2020. – № 2 (120). –P. 93–99. – DOI: https://doi.org/10.36773/1818-1212-2020-120-2.1-93-99.
2. Gremenok, V. F. Solar cells based on semiconductor materials / V. F. Gremenok, M. S. Kuznetsov, V. B. Tivanov. – Minsk : BSU, 2007. – 222 p.
3. Installed Capacity Trends [Electronic resource] / IRENA – International Renewable Energy Agency. – Access mode: https://www.irena.org/Statistics – Access date: 22.08.2021.
4. State cadastre of renewable energy sources [Electronic resource] / Ministry of Natural Resources of the Republic of Belarus. – Minsk, 2020. – Access mode: http://www.minpriroda.gov.by/ru/new_url_-19948904-ru/. – Access date: 22.08.2021.
5. Meshyk, A. Thermal Resources of the Climate of West Polesie, Belarus / A. Meshyk, M. Sheshka, M. Barushka // 7th International Congress on Energy and Environment Engineering and Management (CIIEM7) : Abstracs Book, Canary Islands, Spain, 17–19 July 2017 ; edited by ScienceKnowconferences. – Las Palmas (Spain), 2017. – P. 94–95.
6. Climate Resource Potential to Develop Solar Power in Belarus / A. Meshyk [et al.] // ICBTE 2020. 3S Web Conferences, 212 (2020) 01012. – DOI: https://doi.org/10.1051/e3sconf/202021201012.
7. Meshyk, O. P. Prospects for the development of solar energy in the Republic of Belarus / O. P. Meshyk, M. V. Borushko // Actual problems of Earth sciences: studies of transboundary regions: a collection of materials of the IV International scientific-practical conference assigned to 1000-anniversary of the city of Brest, September 12-14, 2019 / Brest State University named after A.S. Pushkin ; ed. A. K. Karabanova [et al.]. – Brest : BrSU, 2019. – Part 2. – P. 250–253.
8. Meshyk, O. P. Potential climatic resources for the development of solar energy in Belarus / O. P. Meshyk, M. V. Borushko, V. A. Morozova // Comprehensive approach to scientific and technical support of agriculture : materials of the International Scientific and Practical Conference dedicated to the memory of Ya. Bochkareva. – Part I. – Ryazan : RGATU, 2020. – P. 86–91.
9. The efficiency of solar systems (on the example of the climatic conditions of Belarus / O. P. Meshyk [et al.] // Actual scientific, technical and environmental problems of preserving the environment: collection of works of the IV International Scientific and Practical Conference dedicated to the 55th anniversary of the Brest State Technical University and the 50th anniversary of the Faculty of Engineering Systems and Ecology, Brest, October 7-8, 2021 / Brest State Technical University; editorial board: A. A. Volchek [et al.] ; scientific editor A. A. Volchak, O. P. Meshyk. – Brest : BrSTU, 2021. – P. 235–245.
10. Archive of meteorological observations [Electronic resource] / Belhydromet. – Access mode: http://www.pogoda.by/meteoarchive/#. – Access date: 22.08.2021.
11. Shakirov, V. A. Methodology for assessing the arrival of total solar radiation on inclined surfaces using long-term archives of meteorological data / V. A. Shakirov. – Systems. Methods. Technologies. – 2017. – № 4. – P. 115–121.
12. Calculation of the total radiation flux on the inclined plane of solar receivers under conditions of aerosol pollution of the atmosphere / B. I. Nazarov [et al.] // Reports of the National Academy of Sciences of Tajikistan. – 2015. – № 12. – P. 1111–1118.
13. Duffie, J. A. Solar engineering of thermal processes / J. A. Duffie, W. A. Beckman. – Fourth Edition. – Hoboken : John Wiley & Sons, 2013. – 928 p. – DOI: https://doi.org/10.1002/9781118671603.
14. Optimal Tilt Angle and Orientation of Photovoltaic Modules Using HS Algorithm in Different Climates of China / Mian Guo [et al.] // Applied Sciences. – 2017. – Volume 7, Issue 10. – DOI: https://doi.org/10.3390/-app7101028.
15. Mousavi Maleki, S. A. Estimation of Hourly, Daily and Monthly Global Solar Radiation on Inclined Surfaces: Models Re-Visited / S. A. Mousavi Maleki, H. Hizam, C. Gomes // Energies. – 2017. – Volume 10, Issue 1. – DOI: https://doi.org/10.3390/en10010134.
16. Samoilov, D. V. Creation and research of a thermal stabilization system for a greenhouse for the conditions of central Russia : Abstract of a dissertation for the degree of candidate of technical sciences [Electronic resource]. – Access mode: https://static.freereferats.ru/-_avtoreferats/01002979840.pdf. – Date of access: 22.08.2021.
17. Impact of solar panels on global climate / Aixue Hu [et al.] // Nature climate change. – 2016. – № 6. – P. 290–294. – DOI: https://doi.org/-10.1038/nclimate2843.
18. Obukhov, S.G. Choice of parameters and analysis of the effectiveness of the application of tracking systems for the Sun / S. G. Obukhov, I. A. Plotnikov // Bulletin of the Tomsk Polytechnic University. – 2018. – № 10. – P. 95–106.
19. Severyanin, V. S. Meteo-predictive regulation of the temperature regime of premises by automated heating systems / V. S. Severyanin, K. O. Meshyk // Bulletin of the Brest State Technical University. Water management construction, heat power engineering and geoecology. – 2019. – № 2. – P. 74–77.

Accepted 28.10.2021