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ANALYSIS OF ENERGY INDICATORS OF SILICON AND CONCENTRATOR HETEROSTRUCTURE PHOTOELECTRIC MODULES IN CLIMATIC CONDITIONS OF THE MIDDLE ZONE OF UKRAINE

The implementation of distributed generation installations based on renewable energy sources in local power systems requires taking into account their local energy potential, especially for photovoltaic plants with their inherent variable generated power, depending on natural and meteorological conditions.

This work determines and analyzes the energy indicators of solar photovoltaic installations with modules based on crystalline silicon and concentrator A^3B^5 converters for the climatic conditions of the middle band of Ukraine.

Modeling of the annual specific energy production by photovoltaic installations was carried out based on the indicators of the Vinnytsia Hydrometeorological Center. The analysis showed that in this region of Ukraine, economically feasible energy generation by photovoltaic stations can be achieved, and the design scheme of the installation without concentration of solar radiation, but equipped with a system for tracking the position of the Sun, provides an increase in electricity generation compared to a system based on stationary modules. At the same time, the use of concentrator A^3B^5 modules in the considered climatic conditions turned out to be impractical, since this leads to a decrease in electricity generation by more than 7% even compared to a stationary photovoltaic installation based on silicon modules, which is explained by the exclusion of the scattered component of solar radiation from photovoltaic generation and energy losses in the optical concentrator.

The annual distribution of average daily electricity generation by photovoltaic installations with and without solar radiation concentrators in the climatic conditions of Vinnytsia was experimentally investigated.

The analysis of the obtained results showed that in the climatic conditions of the middle zone of Ukraine, photovoltaic installations with a capacity of up to a few kilowatts should be composed of stationary modules of non-concentrated radiation. At the same time, for installations of higher power and photovoltaic stations of the megawatt class, it is worth using schemes with tracking the position of the Sun without concentration of the light flux.

Key words: *photovoltaic panel; solar insolation; concentrated radiation; spatial orientation system; electricity generation.*

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АНАЛІЗ ЕНЕРГЕТИЧНИХ ПОКАЗНИКІВ КРЕМНІЄВИХ ТА КОНЦЕНТРАТОРНИХ ГЕТЕРОСТРУКТУРНИХ ФОТОЕЛЕКТРИЧНИХ МОДУЛІВ В КЛІМАТИЧНИХ УМОВАХ СЕРЕДНЬОЇ СМУГИ УКРАЇНИ

Впровадження установок розподіленої генерації на відновлюваних джерелах енергії в локальних енергосистемах потребує врахування їх місцевого енергетичного потенціалу, особливо для фотоелектричних станцій з притаманною їм мінливою генерованою потужністю, залежною від природних та метеорологічних умов.

В даній роботі визначено та проаналізовано енергетичні показники сонячних фотоелектричних установок з модулями на основі кристалічного кремнію та концентраторних перетворювачів зі сполук A^3B^5 для кліматичних умов середньої смуги України.

Моделювання річного питомого вироблення енергії фотоелектричними установками проведено на основі показників Вінницького гідрометцентру. Аналіз показав, що в даному регіоні України може бути досягнуто економічно доцільне вироблення енергії фотоелектричними станціями, а конструктивна схема установки без концентрації сонячної радіації, але оснащеної системою стеження за положенням Сонця, забезпечує збільшення вироблення електроенергії порівняно з системою на основі нерухомих модулів. В той же час, застосування концентраторних модулів A^3B^5 в розглянутих кліматичних умовах виявилось недоцільним, оскільки це призводить до зменшення вироблення електроенергії на понад 7% навіть в порівнянні з нерухомою фотоелектричною установкою на основі кремнієвих модулів, що пояснюється виключенням з фотоелектричної генерації розсіяної складової сонячного випромінювання та втратами енергії у оптичному концентраторі.

Експериментально досліджено річний розподіл середньодобового вироблення електроенергії фотоелектричними установками з концентраторами сонячного випромінювання та без них в кліматичних умовах м. Вінниці.

Аналіз отриманих результатів показав, що в кліматичних умовах середньої смуги України фотоелектричні установки потужністю до одиниць кіловат доцільно компонувати з нерухомих модулів неконцентрованого випромінювання. В той же час, для установок більшої потужності та фотоелектричних станцій мегаватного класу варто використовувати схеми зі стеженням за положенням Сонця без концентрації світлового потоку.

Ключові слова: *фотоелектричний модуль; сонячна інсоляція; концентроване випромінювання; система просторової орієнтації; електрична генерація.*

Problem Statement

Decentralization of the energy sector with an orientation towards the development of distributed generation is one of the key directions of energy development, the support of which is declared in strategic documents of the state level [1]. The implementation of distributed generation installations based on renewable energy sources in local energy systems requires taking into account their local energy potential, especially for photovoltaic plants (PVs) with their inherent variable generated power, depending on natural and meteorological conditions.

The assessment of the efficiency of solar power plants with tracking devices, but located in different climatic zones, is often impossible due to non-repeatable or difficult to reproduce artificial insolation regimes. Therefore, the calculations mainly use the averaged monthly values of the hourly change in the intensity of the direct solar energy flux under clear sky conditions, given in actinometric reference books. But they also reflect local features of insolation, expressed, for example, by local deviations from symmetry relative to noon. In this regard, it is proposed to carry out an energy assessment using hourly values of the intensity of the direct solar energy flux, calculated using unambiguously regulated parameters of atmospheric transparency.

Analysis of recent studies and publications

The amount of solar energy received by the receiving surface depends on the characteristics of the radiation climate at a given point and the design scheme of the installation [2]. The most energy-efficient design scheme of a photovoltaic power plant is a scheme based on modular photovoltaic installations with two-axis tracking of the position of the Sun [3]. Such a scheme, which was used during the research, is presented in Fig. 1. In it, the photovoltaic installation rotates in height and azimuth for constant orientation to the Sun.

The specified scheme provides for the possibility of using the PV system both with and without solar radiation concentrators. In this installation, which provides the condition $\chi \Rightarrow 0$, where χ – is the angle of incidence of direct solar radiation, every concentrating systems can be applied.

Formulation of the research goal

The goal of this work is to analyze the energy performance of solar photovoltaic installations with and without the two-axis tracking system for the climatic conditions of the middle zone of Ukraine.

Presentation of the main research material

Solar radiation reaches the earth's surface in the form of direct rays from the solar disk (direct solar radiation) and in the form of scattered radiation from the sky (diffuse solar radiation). The sum of direct and scattered radiation reaching a certain surface constitutes the total solar radiation.

Since the area of a solar installation can be different and vary within quite wide limits, it is advisable to calculate the solar radiation inflow per $1m^2$ of the receiving surface of the installation.
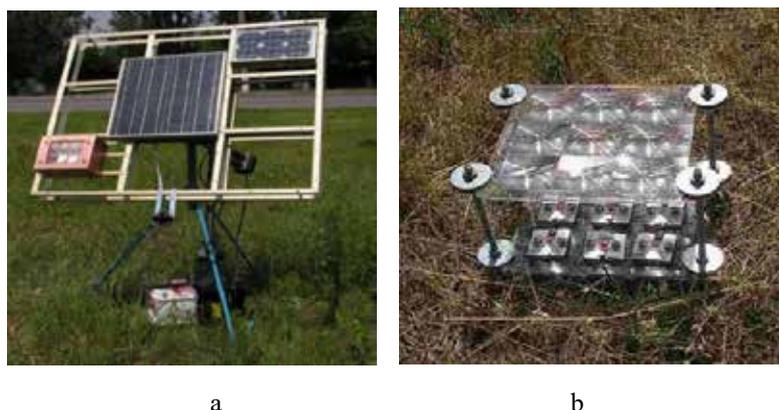
Fig. 1. Photovoltaic installation with two-axis tracking of the position of the Sun (a) and the module of A³B⁵ photovoltaic converters with Fresnel lenses (b)

In general, the inflow of direct solar radiation during the day to a certain fixed or rotating surface can be expressed by the formula:

$$P^*{}_{dn} = \sum_{t_1}^{t_2} \left[(P)r * cos\chi \right], \tag{1}$$

where $(P)r$ is the average inflow of direct solar radiation to a surface normal to the rays for a given time interval in the current month; t_1 and t_2 are the start and end times of irradiation of the surface under consideration by direct solar radiation; χ – is the angle of incidence of direct solar radiation on the surface under consideration at the current time t.

Multiplying P^*dn by the number of days in the current month, we obtain the average monthly inflow of direct solar radiation to the surface under consideration, and summing the monthly values, we find the annual amount.

Similarly, by summing the average hourly values of scattered radiation, it is possible to determine the average daily value of the scattered radiation D^*dn for a given month according to the equation:

$$D^*{}_{dn} = \sum_{t_1}^{t_2} \left[(D)_h (K)_h \right], \tag{2}$$

where $(D)_h$ is the average incoming scattered solar radiation to a horizontal surface for a given time interval in the current month; $(K)_h$ is the conversion factor for the incoming scattered radiation to the surface under consideration, referred to the middle of the current hourly interval for a given month.

The introduction of the specified conversion factor $(K)_h$ is necessary, since information on the average hourly values of scattered radiation is available only for a horizontal surface, and the surface under consideration can be inclined to it at different angles. The value $(K)_h$ is determined by the ratio of that part of the celestial hemisphere that the receiving surface "sees" at the moment to the full hemisphere, which in turn depends on the angle of inclination of the surface under consideration. The part of the celestial hemisphere "visible" by an inclined plane is a spherical dihedral with an angle equal to $(\pi - a)$, where a – is the angle of inclination of this plane to the horizontal surface.

Then, if the angle a is measured in degrees, we have:

$$(K)h = (1 - a/180)h. \tag{3}$$

Formula (3) is obtained under the assumption of uniform distribution of scattered radiation over the celestial hemisphere, which is quite valid, especially in the case of a completely clear sky. However, this assumption is the only possible one, since there are no reliable statistical models of the distribution of scattered radiation over the sky, especially for the sky partially or completely covered by clouds. The average daily sum of the total radiation is determined by adding the right-hand sides of expressions (1) and (2). When using these expressions, the values of $P^*{}_{dn}$ and $D^*{}_{dn}$ can be taken from [4], and the values of $(1 - a/180)_h$ must be calculated.

For the angle of incidence of solar rays the expression [5] is valid:

$$cos\chi = sin\,h\,cos\,a + cos\,h\,cos\,A\,sin\,a , \tag{4}$$

where h and A are the height of the Sun and its azimuth at a given time.

However, h and A are themselves functions of the latitude φ, time of day t and season, which can be expressed in terms of the declination of the Sun δ. Omitting intermediate transformations, we arrive at the equation:

$$\cos\chi = \sin\delta\left[\sin\varphi\cos a + \sin a\left(\sin\varphi\,\mathrm{tg}\varphi - \frac{1}{\cos\varphi}\right)\right] + (\cos\varphi\cos a + \sin\varphi\sin a)\cos\delta\cos t \ . \tag{5}$$

For the installation shown in Fig.1(a), which is a system with automatic orientation to the position of the Sun, $\chi = 0$, and the value $(1 - a/180)_h$ is found according to the equation:

$$\left(1 - \frac{a}{180}\right)_{\text{год}} = 1 - \left[90 - \arcsin\left(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos t\right)\right]/180 \ . \tag{6}$$

Thus, using formulas (1)–(6), it is possible to calculate the direct, diffuse, total solar radiation on the receiving surface of a modular photovoltaic installation for any given time interval.

The next stage of calculations is to determine the electricity generation by a photovoltaic installation. Not all solar energy that has reached the surface of the installation can be effectively converted into electricity. Regarding photovoltaic converters (PVCs), the limiting factor is the voltage, which at a low solar radiation flux density decreases below the nominal level, which makes it impossible to meet the needs of the consumer. Therefore, solar energy that arrives at a flux density less than a certain "threshold" value cannot be used.

Taking into account the above, the calculation of the average daily electricity production in a certain month in specific terms, i.e. per 1m^2 of the receiving surface of the photovoltaic module, for installations with solar radiation concentrators is carried out according to the formula:

$$A_{dn}^* = P_{dn}^*(\eta)_0 \ , \tag{7}$$

where $(\eta)_0$ – efficiency of the optical concentrating system (taken at the level of 0.875); η – efficiency of conversion of solar energy into electricity, the value of which for the studied silicon PVs was taken equal to 0.188, and for concentrator A^3B^5 PVs – 0.236 [6].

The calculation in specific terms is universal, since the electricity generation of a particular designed installation can be easily calculated by multiplying the specific generation by the receiving area of this installation. For a specific installation with known values of $(\eta)_0$ and η, the electricity generation is found by proportional conversion.

The average daily specific electricity generation in the calculated month by photovoltaic installations without solar radiation concentrators is determined by the expression:

$$A_{dn}^* = (P_{dn}^* + D_{dn}^*) \ , \tag{8}$$

in which D^*dn takes into account the limitations on the maximum density of scattered radiation.

Knowing the average daily specific electricity generation in each month, it is not difficult to determine the energy generation throughout the year.

Calculations according to the above-mentioned method were carried out by the Regional Hydrometeorological Center of Vinnytsia (49.23 N). The entire array of calculation results is presented in a table, which shows the value of the specific annual electricity production for a photovoltaic modular installation, made according to the structural scheme of Fig. 1 with solar radiation concentrators (K) and without them (B/K). Data on the estimated annual electricity production are presented in Table 1.

Table 1

Estimated annual electricity production PVCs, kWh/m2

Point Geographical	Latitude, degrees N	Stationary (B/K)	Tracking (K)	Tracking (B/K)
Vinnytsia	49.23	154.2	142.4	206.0

The obtained calculation results confirmed the a priori qualitative statement that the volume of electricity generation by photovoltaic installations is greater in the area where the solar climate is more favorable [7]. Thus, from the data in Table 1 it is clear that in the considered region of Ukraine, which belongs to the "solar" region, economically justified energy generation can be achieved [8]. However, quantitative indicators for this region regarding the volume of energy generated using installations with a two-axis system for tracking the position of the Sun were obtained for the first time.

From the data presented in Table 1, it also follows that in the absence of solar radiation concentrators, the design scheme associated with the rotation of photovoltaic modules provides an increase in electricity generation compared to a fixed module. At the same time, the use of concentrating systems reduces electricity generation both by eliminating the scattered component of solar radiation and due to losses in the optical concentrator.

Reduction of specific annual energy generation for a scheme with a concentrator compared with a fixed scheme is more than 7%. Increasing the efficiency of photovoltaic installations with concentrators at a fixed level of photovoltaic

conversion efficiency is possible only by increasing the efficiency of the concentrating system $(\eta)_0$. For example, if $(\eta)_0$ is increased from the value adopted in the calculation of 0.875 to 1, electricity generation will increase by 12.5%.

From the data in Table 1 it also follows that the scheme, which involves the orientation of the photovoltaic module without the concentration of the light flux, gives the best results, which is quite natural, since the condition $\chi = 0$ is met.

Since the data available in the literature on the parameters of PVCs at low illumination are contradictory, relate to different types of PVCs and therefore cannot be taken as a reliable basis, this circumstance required the setting up of an experiment, which was carried out on a laboratory stand, the block diagram of which is presented in Fig. 2. The information was recorded on a recorder during the calendar year 2021.
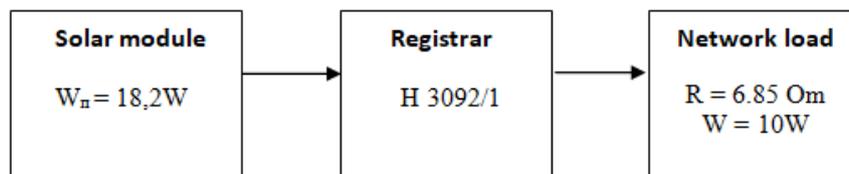

Fig. 2. Block diagram of the laboratory stand

The object of the study was silicon PVCs obtained from rice husks, as well as concentrator A^3B^5 PVCs with Fresnel lenses [6].

It has been established that when using solar concentrators, the flux density of direct solar radiation on the module surface is always higher than the threshold value. Thus, all direct solar radiation arriving at the module surface can be converted into electrical energy and used in the load.

For photovoltaic installations without concentrators, in the presence of direct solar radiation, the fraction of radiation with a density less than the threshold is small. However, in the absence of direct solar radiation, the influx of scattered radiation with a flux density less than the threshold value can constitute a significant part of the total influx of scattered radiation. As the analysis has shown, such a decrease depends only on the climatic indicators of the location of the PV plant. It is more significant for areas characterized by the largest fraction of scattered radiation in the influx of solar energy. The specified restriction on the threshold value of the scattered radiation flux density reduces the total annual intake of total radiation that can be converted into electricity by 10-20%.

The nature of the energy source used by photovoltaic installations is such that its intake varies in daily and annual intervals. Accordingly, the power of the installations and their electricity generation also change. Daily patterns of power changes are more clearly visible during a clear day. The annual course of electricity generation is significantly affected by both the latitude factor and the climatic characteristics of the location of the PV plant.
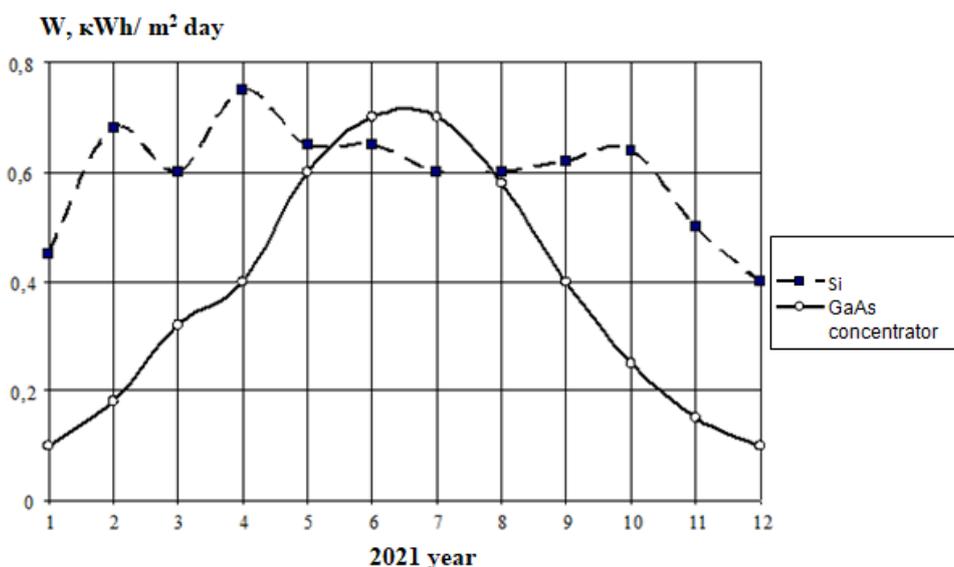

Fig. 3. Distribution of specific electricity generation by months (Vinnytsia, 2021)

Fig. 3 represents the annual course of the specific average daily electricity generation by a photovoltaic installation in the climatic conditions of the city of Vinnytsia ($\varphi = 49.23°$ N) according to the results of measurements during 2021.

It is worth noting that the obtained experimental values of monthly and annual energy generation by photovoltaic installations are the upper limit of these values, since such factors as energy consumption for the PV plant's own needs, for example, for rotating modules, the discrepancy between the real load and the maximum power point on the ampere-voltage characteristic of the photovoltaic installation, energy losses in the inverter that converts direct current into alternating current of the required frequency and voltage, etc. are not taken into account.

Conclusions

A comparison of the efficiency of various design schemes of modular photovoltaic installations leads to conclusions that are significant for practice.

Thus, the use of solar radiation concentrators allows to significantly reduce the consumption of photoconverters per unit of installation power but leads to a decrease in the specific annual electricity generation even in comparison with a stationary photovoltaic module.

The use of systems with optical concentrators reduces the average annual electricity production compared to modules of non-concentrated solar radiation due to the exclusion of the scattered component of solar radiation from the process of photovoltaic conversion and the presence of energy losses in the concentrators. Thus, in the climatic conditions of Vinnytsia, the reduction in specific annual energy production for a scheme with concentrators compared to concentrator-free installations ranges from 7% to 30%, depending on whether the modules of non-concentrated radiation are equipped with a system for tracking the position of the Sun.

The efficiency of photovoltaic installations with concentrators can be increased at a fixed photovoltaic conversion efficiency by increasing the efficiency of the concentrating system $(\eta)_0$. Thus, with an increase in $(\eta)_0$ from 0.875 to 1, electricity production will increase by 12.5%.

Therefore, in the climatic conditions of the middle zone of Ukraine, photovoltaic installations of low power, up to units of kilowatts, are advisable to be composed of stationary modules. At the same time, for installations of higher power and megawatt-class photovoltaic power plants, from an energy point of view, it is advisable to use schemes with tracking the position of the Sun without radiation concentration.

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