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Improving the energy characteristics of a solar photoelectric station of spherical and cylindrical surface shapes for the power supply of remote rural areas and agricultural enterprises

Dmitry Strebkov[1], *Yuriy* Shogenov[2], *Ahmet* Penjiyev[3], *Besarion* Meskhi[4], and *Dmitry* Rudoy[4*]

[1]Federal Scientific Agroengineering Center VIM, 5, 1st Institutskiy Proezd, Moscow, 109428, Russia
[2]Russian Academy of Sciences, Mechanization, Electrification and Automation Sector of the Department of Agricultural Sciences, 32A, Leninskiy Prospect, Moscow, 119334, Russia
[3]Turkmen State Institute of Architecture and Civil Engineering, 4/1, Gunesh, Bikrova, Ashgabat, 744000, Turkmenistan
[4]Don State Technical University, 1, Gagarin Square, Rostov-on-Don, 344003, Russia

Abstract. One of the actual tasks of generating electricity is to increase the energy efficiency of solar photoelectric stations (SPS) in uneven lighting. The purpose of the work is to study the energy characteristics of the SPS under uneven lighting to improve the energy efficiency of solar power plants, including those for agro–industrial enterprises located and operating in remote rural areas, on sloping lands, mountainous and foothill terrain, where the efficiency of the SPS can be higher than on the plain due to a higher level of illumination. The methods of mathematical analysis with application of geometric optics, photoelectric conversion methods and construction physics in solar engineering are used. Analytical calculations were carried out to clarify the design parameters of the SPS that are made in the form of a sphere and a cylinder. The article presents the results of theoretical studies of the electrical characteristics of SPS made in the form of a sphere and a cylinder under uneven illumination of solar photoelectric modules (SPM). The relationship of electrical power and the number of SPS in the SPS is determined by the methods of mathematical statistics. As a result of studies of the electrical characteristics of SPS in uneven lighting, the following results were obtained: for SPS in the form of a sphere, small-area SPS have energy efficiency 32% more than large-area SPS; for SPS in the form of a cylinder of small-area SPS, energy efficiency increases by 19% compared to large-area SPS. The relationship between electrical power and the number of SPS was determined using the coefficient of determination, which is equal to: for a spherical surface - 36.2%, for a cylindrical one - 26.6%.

1 Introduction

* Corresponding author: dmitriyrudoi@gmail.com

Currently, due to the exhaustion of energy resources and the negative impact of traditional energy on the environment, the volume of use of renewable energy sources (RES) is increasing [1]. One of the prospective areas is the use of energy systems that are based on obtaining an incident light flux and converting solar energy into electrical energy. The use of solar photoelectric stations (SPS) is especially relevant for remote rural areas, farms and agricultural enterprises, including pastures, farms and facilities located in mountainous areas (where there is a lot of light) and slope cultivated lands. At the same time, it is necessary to achieve the best competitive energy characteristics of the SPS [2-5].

For example, autonomous power supply systems in pastures allow milk to be completely processed on site for sour cream, cheese, butter and other dairy products. At the same time, there is no need to transport milk to specialized processing enterprises that are sufficiently remote from pastures, thus precious time is saved.

According to the estimates of the European Energy Commission, about three million places of work will be created in the EU countries using renewable energy technologies. The use of renewable energy technologies can increase the gross domestic product (GDP) by 1.1% [6, 7].

According to the German Federal network agency, in 2020, the share of solar energy in electricity generation in the country exceeded 10% for the first time. At the same time, the total share of renewable energy sources (RES) in electricity generation in 2019 exceeded the share of coal and nuclear power plants according to the Institute of Solar Energy Systems of the Fraunhofer Society (Fraunhofer ISE).

In rural areas, SPS are installed on farm fields and agricultural lands (for example, in Germany, Japan, France, Italy, Greece, etc.). The architectural placement of SPS is pre-designed taking into account the possibilities of eliminating the risks of their location on the ground and the features of the negative impact of the falling shadow on the growth and development of crops during the growing season.

By the end of 2019, the installed capacity of the global solar energy reached 629 GW and 115 GW of solar photoelectric plants were built during 2019, according to the "Snapshot of global PV Markets 2020" report from IEA PVPS [8].

China has 30.1 GW of solar power plants installed, followed by the USA – 13.3 GW, and India – 9.9 GW. These countries, traditionally, have become the largest markets. Approximately 16 GW were commissioned in the European Union, the largest markets were Spain – 4.4 GW and Germany - 3.9 GW. Asia accounted for about 57% of the total new SPS capacity, including countries such as South Korea, Taiwan, and Malaysia. In the UK in 2020, 10 million homes had solar photomodules [7].

The decision of the European Parliament states that it is necessary to reduce greenhouse gas emissions in the European Union by 40%. This will give a great impulse to further increase the use of solar energy in the European Union and the implementation of the Paris Agreement on Climate Change [7, 9].

The Ministry of Energy of the Russian Federation predicts that by 2024, electricity from renewable sources will account for 4.5% of the total electricity generation in the country. At the same time, the installed capacity of such stations should reach 25 GW, and by 2030 these indicators in the Russian Federation should grow to 10% of the total output in the country and the installed capacity will be 100 GW [6.10].

According to the International Energy Agency (IEA), 19,000 GW of solar modules will be installed worldwide by 2050, of which 30% will be installed on roofs and facades of buildings [11]. The use of SPS in the agricultural sector allows to solve a relatively large range of tasks for providing electricity to buildings, structures and various electrical equipment (separators, grain cleaners, pumps, electric knives, electric motors, etc.), taking into account the availability of free territories and significant total areas of roofs and walls of agricultural production facilities (livestock complexes, greenhouses, buildings, etc.). At the same time, the energy efficiency of SPS should be high enough (the higher, the better) to reduce their payback period and increase the profitability of the agricultural products received.

For more efficient use of solar photomodules in solar power plants, various methods and systems are used to increase their energy efficiency:

- use of solar cells (SE) with improved technical characteristics;
- systems of continuous automatic tracking of solar photoelectric plants for the Sun;
- system regulation of the maximum power according to the volt-ampere characteristic of solar photoelectric modules (SPM);
- optimization of the size of the SPM and the shape of the receiver surface [2-5].

The efficiency of using solar energy in modern solar systems is determined by the features of their architecture, the orientation of the station, the position of its elements relative to the southern direction and the plane of the surface horizon, the choice of materials and engineering structures, including fences [6, 7, 10, 12, 13].

There is an increasing interest in solar architecture and the shape of the SPS structure. At the same time, new solutions arise, which often converge with the traditional ideas of classical architecture [7, 10, 11-15].

In addition to all the requirements, the solar architecture should provide maximum sunlight in winter in order to reduce fuel consumption and reduce overheating in summer. Based on this, energy saving based on solar energy technologies is one of the most actual problems in energy production from the point of view of the economy, ecology and the overall technological level of the country's development [6,8-10,14,16-19].

The physical basis of the construction of solar engineering systems lies in the fact that the spherical surface ensures uniform distribution of loads at all points equally and works for compression and deflection, thereby has a number of advantages: withstands wind and snow loads; has the largest volume with the smallest surface area; and minimal heat losses, which are four times less in terms of compared to the surface of a cube of the same volume. Compared with cubic forms, such spherical solar systems are characterized by increased seismic resistance, lower material consumption of the structure, less labor intensity in manufacturing and outwardly more perfect in their aesthetics when performed in various spherical ensembles [7,10-13,15,20].

In most studies on the use of solar photoelectric stations, calculation of their structural and energy characteristics, traditional flat structures are considered [21-24]. The article for the first time considers the features of architectural planning and design solutions of the SPS, made in the form of a hemisphere or a half-cylinder using the SPM in order to determine the dependence of the electrical power of the SPS on the size of the SPM [10, 15, 25].

The purpose of the work is to study the energy efficiency of SPS when illuminating the surface of SPS solar engineering structures and structures of spherical and cylindrical shapes.

The methodology of the research consists of methods of physical, mathematical analysis using geometric optics, methods of photoelectric transformation and construction physics in solar engineering. Analytical calculations were carried out to clarify the design parameters of SPS spherical and cylindrical shapes, as well as to obtain comparative design indicators of their energy efficiency.

2. Materials and methods

When installing the SPM on a non-planar surface, we obtain a three-dimensional SPS structure illuminated by a parallel radiation flux with a density of P0. The power of the SPM varies from zero to P_{max} depending on its orientation to the Sun. The electrical power of the SPM with serial switching of the SPS is determined by the electrical power of the least illuminated SPM [7, 9, 11, 14, 26].

In recent years, much attention has been paid to the creation of solar houses made in the form of a hemisphere or a half-cylinder [12].

2.1 Spherical surface of the SPS

When installing the SPM on a non-planar surface, we obtain a three-dimensional SPS structure illuminated by a parallel radiation flux with a density of P0. The power of the SPM varies from zero to P_{max} depending on its orientation to the Sun. The electrical power of the SPM with serial switching of the SPS is determined by the electrical power of the least illuminated SPM [7, 9, 11, 16, 26, 27].

The scheme for calculating the electric power of a spherical SPS, the location of the vectors $\overline{P}$, kW/m^2, and $\overline{n}$ in the Cartesian (a) and polar (b) coordinate systems are shown in Figures 1, 2:

a) The radiation flux directed parallel to the y-axis is determined by:

$$\overline{P}=P_0\,\overline{j}, \tag{1}$$

where P_0 is the energy illumination at the normal orientation of the SFM, equal to 1 kW/m^2;

$\overline{j}$ is a unit vector along the y-axis.

The unit vector of the normal $\overline{n}$ to the surface of the sphere (Figure 1) is equal to:

$$\overline{n}=\{cos\alpha,\ \ cos\beta,\ cos\gamma\}=\left\{\frac{x}{R_c},\ \frac{y}{R_c},\ \frac{z}{R_c}\right\}, \tag{2}$$

where Rc is the radius of a quarter of the sphere, at point A with coordinates (x, y, z), m (Figures 1 and 6).

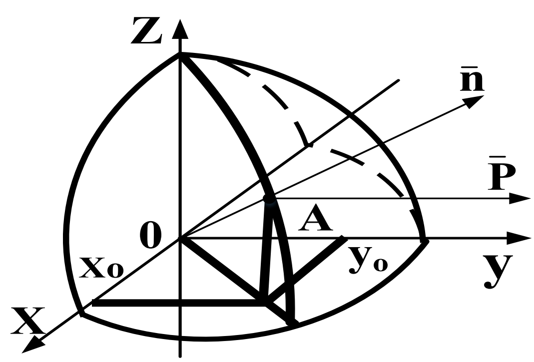

Fig. 1. Diagram of the arrangement of the solar radiation flux ($\overline{P}$) and the unit vector to the normal surface ($\overline{n}$) in the Cartesian coordinate system.

b) Lines of level L of equal illumination, (Figure 2):

$$\left\{\begin{matrix} y=y_0=const \\ x^2+y^2+z^2=R_c^2 \end{matrix}\right\}\ or\ L:\ x^2+z^2=r^2, \tag{3}$$

where R_c - radius of the sphere surface, m; $r^2=R_c^2-y_0^2$;

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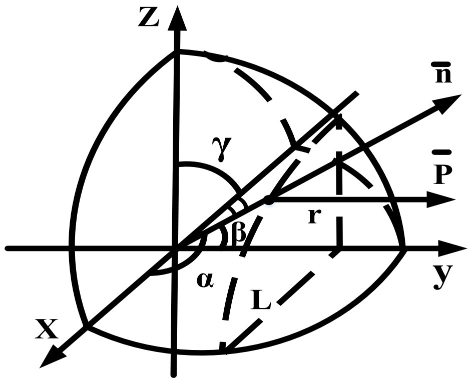

Fig. 2. A diagram for calculating the electrical power of a spherical SPS in a polar coordinate system, with the location of solar radiation vectors $\bar{P}$, and normal sphere surface $\bar{n}$.

b) Total number N of SPS photomodules on the sphere surface (Figure 3):

$$N_1 = \frac{4\pi R_c{}^2}{K_z a^2}, \tag{4}$$

where K_z – fill coefficient;
a – photomodule linear size, m;
$S_M = a^2$– photomodule square, m^2.

c) The number of photomodules placed on the quarter circle of the axial section $N = \pi R/2a$, (Figure 4) is described by the equation S:

$$\begin{Bmatrix} x^2 + y^2 + z^2 = R_c^2 \\ y \geq 0, \\ z \geq 0 \end{Bmatrix} \tag{5}$$

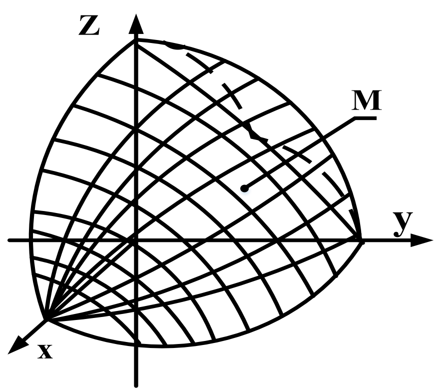

Fig. 3. The layout of the photomodules M on the SPS surface.

Full electric power of SPS, P_{SPS}, kW, proportional to the vector flux $\bar{P}$ through the surface S:

$$P_{SPS} = 2\,\eta \iint_s (\bar{P}, \bar{n})dS, \text{ kW} \tag{6}$$

where η is the efficiency factor of the photomodule under normal conditions, %;
$\bar{P}$ - solar radiation flux vector, kW;
$\bar{n}$ - unit vector to the normal of the sphere surface;
S - the square of the quarter sphere, m^2, equal to $S_{1/4} = \pi R^2$.

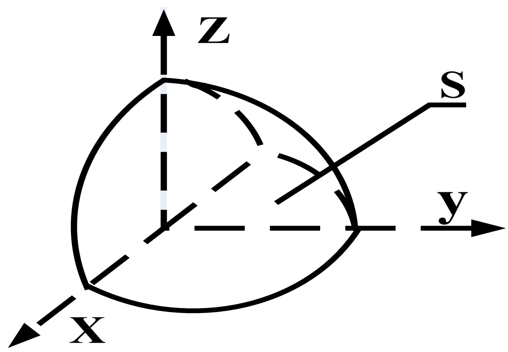

Fig. 4. Diagram of a quarter spherical surface (S) for arranged photomodules in Cartesian coordinates.

When the radiation flux is perpendicular to the SFM plane or vectors $\bar{P}$ and $\bar{n}$ are collinear $\bar{P} = æ\bar{n}$; æ – proportionality coefficient, $\iint_s (\bar{P}, \bar{n}) dS$ – the second-order surface integral of the scalar product of $\bar{n}$ and $\bar{P}$ on the surface S [15,28].

e) When calculating the integral, we assume (Figure 5):

1. Electrical power P_{SPS} is equal to the sum of the electrical capacities of the photomodules:

$$P_{SPS} = \sum_{n=1}^{M} P_{PC}, \text{ kW} \tag{7}$$

Photomodule electrical power P_{PC} is proportional to the radiation flux at minimum illumination:

$$P_{PC} = \eta \iint_{S_n} min(\bar{P}, \bar{n}) dS_n, \text{ kW} \tag{8}$$

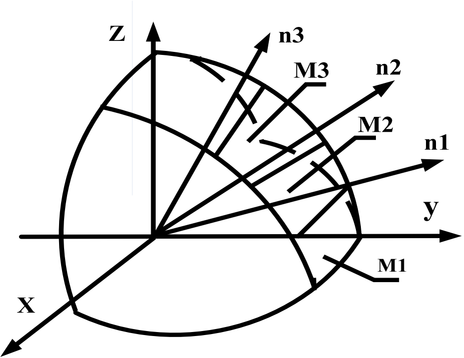

Fig. 5. Arrangement of photomodules M1, M2, M3 and vectors to the normal n1, n2, n3 surface of the quarter sphere.

f) Because $(\bar{P}, \bar{n}) = P_0 \cos\beta_n$;

$$P_{пм} = \eta\, P_0 \iint_{S_n} min\, cos\beta_n\, dS_n\,,\ \text{kW} \tag{9}$$

where $min\ cos\beta_n = cos\max\beta_n = cos\frac{\pi n}{2N}$
n – the number of photomodules M on the surface of the sphere.
Then the electrical power of the photomodules P_{SPS} is equal to

$$P_{SPS}=2\eta\, P_0 \sum_{n=1}^{N} cos\frac{\pi n}{2N} \iint_{Sn} dS_n\,,\ \text{kW} \tag{10}$$

where S_n – the surface of the photomodules located on the surface of the sphere between the lines of the level of equal illumination n (Figures 5 and 6) the location of the photomodules M1, M2, M3 on the surface of the quarter of the sphere (7) and the line of the levels of equal illumination (8):

$$r^2_{n-1} < x^2_n + z^2_n < r^2_n, \tag{11}$$

$$r^2_n = R^2 - y^2_n = R^2 - R^2 cos^2\beta_n = R^2 sin^2\beta_n;\ r_n = R\,sin\beta_n; \tag{12}$$

$$\iint_{S_n} dS_n = \iint_{S_{on}} \frac{dx_n\, dz_n}{cos(\overline{n}, \overline{y_n})}, \tag{13}$$

where S_{0n} is a projection of S_n onto a plane XOZ,

$$\iint\limits_{S_{on}} \frac{dx_n\, dz_n}{cos(\overline{n}, \overline{y_n})} = \iint\limits_{S_{on}} \frac{dx_n\, dz_n}{\frac{y_n}{R}} = R \iint\limits_{S_{on}} \frac{dx_n\, dz_n}{\sqrt{R^2 - x^2_n - z^2_n}} \tag{14}$$

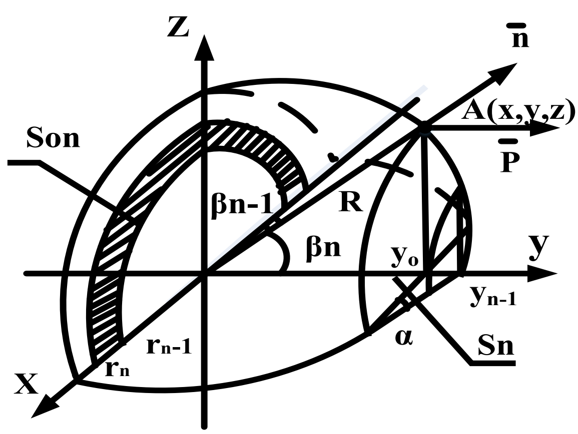

Fig. 6. A scheme of linear levels of equal illumination on a quarter of the surface of a sphere for calculating the electrical power of a spherical SPS.

Transition to polar coordinates:

$$x_n = r_n\, cos\,\varphi;\ z_n = r_n sin\varphi,\ r_n = \sqrt{x^2_n + z^2_n} = \sqrt{R^2 - y^2_n} = R sin\beta_n,\ n=1,2,3\ldots \tag{15}$$

By definition, consider $r_0 = 0$:

$$R \iint_{S_{0n}} \frac{dx_n\, dz_n}{\sqrt{R^2 - x_n^2 - z_n^2}} = R \iint_{S_{0n}} \frac{r_n dr_n}{\sqrt{R^2 - r_n^2}} = -\frac{R}{2} \int_0^{\pi} d\varphi \int_{r_{n-1}}^{r_n} \frac{d(R^2 - r_n^2)}{\sqrt{R^2 - r_n^2}} =$$

$$\frac{R}{2} 2\pi \sqrt{R^2 - r_n^2} \,|_{r_n}^{r_{n-1}}\, R\left(\sqrt{R^2 - r_{n-1}^2} - \sqrt{R^2 - r_n^2}\right) \pi R (y_{n-1} - y_n) =$$

$$= \pi R^2 \,(\cos\beta_{n-1} - P_0 \pi R^2 \sum_{n=1}^{N} \cos\beta_n (\cos\beta_{n-1} - \cos\beta_n), \text{ kW}, \quad (16)$$

where $\beta_n = \frac{\pi n}{2N}$, $\beta_0 = 0^o$.

If a $\geq \frac{\pi R}{2}$, $N \leq 1$, $\cos\frac{\pi n}{2N} = \cos\frac{\pi}{2} = 0^o$. $P_{SPS} = 0$; where $N = 2$:

$$\sum_{n=1}^{2} \cos\beta_n (\cos\beta_{n-1} - \cos\beta_n) = \cos\pi/4 \;(\cos\, 0^o - \cos\pi/4) = 0{,}21, \quad (17)$$

$$P_{SPS} = 0{,}42\eta\, P_0 \pi R^2 \text{,kW} \quad (18)$$

Maximum power $P_{SPS,max}$, corresponds to the area of the photomodule with uniform illumination. This is confirmed by the fact that the area of the photomodule decreases to a point $a_M \rightarrow 0$ where $N_M \rightarrow \infty$.

$$P_{SPS\,max} = \lim_{N\to\infty} 2\eta P_0 \sum_{n=1}^{N} \iint \cos\left(\frac{\pi n}{2N}\right) dS = 2\eta P_0 \iint_s \cos\beta dS = 2\eta P_0 \iint_{S_0} \cos\beta \frac{dz\, dx}{\cos(\bar{n},\,} \quad (19)$$

where S_0 is a projection of S onto a plane XOZ.

Equation S_0:

$$\begin{cases} x^2 + z^2 \leq R_{SP}^2 \\ y = 0, \\ z \geq 0 \end{cases} \quad (20)$$

Because $\cos(\bar{n}, \bar{y}) = \cos\beta$, and $\iint_{S_0} dzdx = \frac{\pi R^2}{2}$, $P_{SPS\ max} = \pi R^2 \eta P_0$, the ratio of electrical power, $\frac{P_{SPS}}{P_{SPSmax}}$, is equal to (o.e.):

$$\frac{P_{SPS}}{P_{SPSmax}} = 2\sum_{n=1}^{N} \cos\beta_n \left(\cos\beta_n - \cos\beta_{n-1}\right), \quad (21)$$

where $\beta_n = \frac{\pi R}{2N}$, $\beta_0 = 0^o$.

Large area solar photoelectric module: $a^2 = 0{,}1\text{m}^2$; $a = \sqrt{0{,}1} = 0{,}33$ m; R = 1m; $N = \frac{\pi R}{2a} = 4{,}7$.

Dependence of electrical power P_{SPS}/P_{SPSmax}, kW, on the ratio R/a is shown in the Table 1.

Table 1. Change in electrical power P_{SPS}/P_{SPSmax}, from the size and number of modules on the surface of the sphere R/a.

The number of photomodules on the surface of the quarter sphere	1	2	3	4	6	12	∞

Electrical efficiency in terms of power, kW	0	0,42	0,62	0,70	0,75	0,78	0,91

Small area solar photoelectric module: $a=0,06$ m; $R=1$m; $N = 26,1$.

Taking into consideration the photomodule size $a_{m2} = 0,6$ м и $a_{m1} = 3$ м, we get for a sphere of radius $R_{sp} = 10$ m; $N_{fn1} = 4,7$; $N_{fn2} = 26,1$; $\frac{P_{fp1}}{P_{fp2}} = 0,75$, that is, reducing the size of solar modules in a spherical SPS increases the generation of electrical energy by 32% [15,28].

2.2 Cylindrical surface of SPS

A similar calculation for a cylinder has the form as the following:

$$P_{SPS} = 2H\eta P_0\ R_C \sum_{n=1}^{N} cos\beta_n(\beta_n - \beta_{n-1}) = 2H\eta P_0\ R_C \sum_{n=1}^{N} y_n(\beta_n - \beta_{n-1}),\ \text{kW} \quad (22)$$

where H is cylinder height, m.

$$N = \frac{\pi R_C}{2a},\ \beta_n = \frac{\pi n}{2N},\ \beta_0 = 0^o; \quad (23)$$

$$P_{SPS\,max} = \eta P_0 \pi R^2{}_C = P_{ax.sec.}; \quad (24)$$

$$\frac{P_{SPS}}{P_{SPSmax}} = 2\sum_{n=1}^{N} cos\,\beta_n\ (\beta_n - \beta_{n-1}), \quad (25)$$

The scheme for calculating the electrical power of an oriented cylindrical SPS is shown in Figure 7.

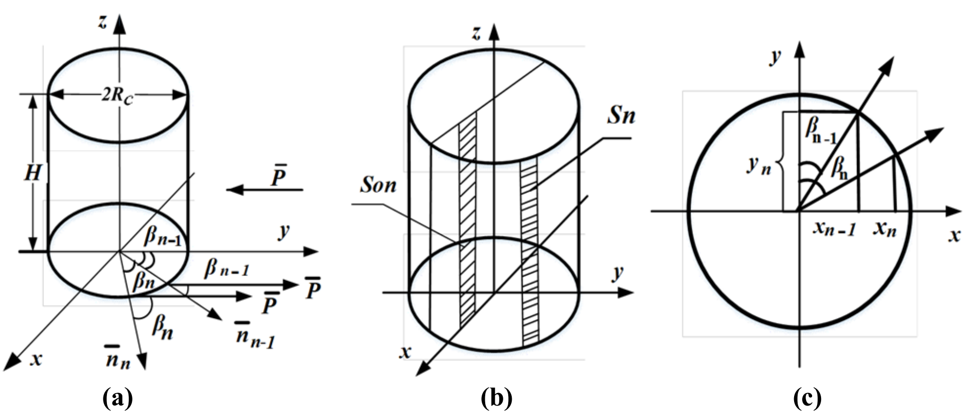

Fig. 7. SPS in cylindrical coordinates (a) and the boundaries of uniform illumination (b), determining the angle β (c).

3 Results

The change in electrical power and energy efficiency of spherical and cylindrical SPS depending on the size of the elementary module is shown in Table 2.

Table 2. Energy efficiency of SPS photomodules depending on the size and number of modules on the surface of the sphere and cylinder.

The number of photomodules on the surface of a sphere or cylinder	1	2	3	4	5	6	12	∞
Electrical efficiency by cylinder power, kW	0	0,55	0,70	0,80	0,83	0,87	0,97	1
Electrical efficiency by sphere power, kW	0	0,42	0,62	0,70	0,74	0,78	0,91	1

In the experience of scientific research, there is a need to approximate the scattering dynamics in the form of a mathematical equation. The mathematical expression of correlation dependence is called regression equations. Using mathematical calculations, we obtained regression equations for the dependence of electrical power on the number of modules on the surfaces of the sphere and cylinder, which are, for:

$$\text{- spherical form } y = 0{,}0648x+0{,}2918,\ R^2 = 0{,}6017; \quad (26)$$

$$\text{- cylindrical form } y = 0{,}0646x+0{,}3745,\ R^2 = 0{,}5158. \quad (27)$$

The proximity of the relation between electrical power and the number of photomodules was determined on the basis of the coefficient of determination, which determines part of the variation in electrical power indicators and the number of modules on a spherical surface, while the correlation coefficient R^2 = 0,6017, and for cylindrical surface R^2 = 0,5158. The coefficient of determination for a spherical surface is equal to 36.2%, for cylindrical 26,6%.

Consequently, 36.2% the relationship of the electrical power of the photomodule depends on the surface size of the number of photomodules. The remaining 63.8% of the variation depends on the influence of other unaccounted factors. The coefficient of determination for a cylindrical surface the relationship of the electrical power of the photomodule depends on the surface size of the number of photomodules is equal to 26.6%, 73.4% of the variation depends on the influence of other factors not taken into account.

For the considered sizes of modules and a cylinder of radius of R_C = 10 м, Pfn_1/Pfn_2 = 0.84, that is, the use of small-area SPS increases the energy-producing capacity of the SPS by 19% [10, 13].

4 Discussion

The energy characteristics of the SPS in the form of a sphere and a cylinder under uneven illumination on the surface of solar buildings and structures are estimated.

As a result of theoretical studies of the electrical characteristics of spherical and cylindrical SPS with their uneven illumination, the following conclusions were obtained:

- spherical SPS with a small area of SPM has a power and electrical efficiency 32% greater than SPM with a large area;
- for cylindrical SPS from small-area SPS, electrical power and electrical efficiency increases by 19% compared to large-area SPS;
- the energy characteristics of SPS of cylindrical surface shape are more efficient than SPS of spherical shape by an average of 14-15% with the same area of photoelectric modules.
- the results obtained can be used for practical calculations in the design and construction of solar power plants for power supply to remote rural areas, farms and

enterprises of the agro-industrial complex, including pastures, farms and other agricultural structures located in mountainous areas, plains and sloping agricultural lands;

- the data obtained are also significant in the construction of space-based and ground-based solar photoelectric installations, including buildings and structures that are used in various architectural variations of SPS as an additional or alternative source of electrical energy;
- in the future and currently, for remote rural areas, mountainous and foothill areas, autonomous power supply systems with SPS are very relevant for practical purposes for additional provision of lighting network and power and loads;
- the use of SPS for power supply of residential buildings, industrial and agricultural facilities reduces energy consumption from traditional, environmentally insufficiently clean fuel power plants and makes a significant contribution to the fight against environmental pollution and global warming.

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