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DEFINITION OF THE DAILY MODEL OF DISTRIBUTION OF SOLAR RADIATION ON THE CURVED SURFACES OF BUILDINGS

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Abstract

The development of the integration of renewable energy into the energy supply of buildings leads to the formulation of the problem of efficient placement of solar thermal devices on surfaces of complex shapes (shells). An urgent task is the development of tools that can justify the decision-making by designers about the advisability of placing solar thermal devices and their implementation in the energy-efficient design of buildings. The study solves the problem of finding zones on the surface of the envelope, receiving the maximum amount of solar radiation during a given period of time – an epoch. A method is applied based on discrete geometric modeling of solar radiation input to curved surfaces of buildings. In this case, the interaction of a set of design parameters is taken into account: parameters of the shape of a curved surface and parameters of variable sunlight for the characteristic dates of September 21, March 21 – the solar equinox and December 21, June 21 – the winter and summer solstices. In the course of the study, N is determined – the optimal number of fixed positions of the Sun on the solar trajectory for different angles of solar declination (for June 22 $N = 17$, for September 21, March 21 $N = 11$, for December 21 $N = 8$), for a given geographical location. One of the examples of modeling the amount of solar radiation entering the surface of a hyperbolic paraboloid during the day at the geographical latitude $\delta = 52°$ (Kyiv, Ukraine) is shown. The simulation results in a family of lines of the same level of solar radiation on a curved surface during the day. Using the values of the averaged daily model, it is possible to proceed to obtaining averaged daily models for the estimated time interval at the stage of pre-project proposals to predict the efficiency of using the solar system.

Keywords: solar radiation, curved surfaces of buildings, renewable energy, discrete geometric modeling.

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1. Introduction

With a sharp reduction in the reserves of non-renewable energy sources and a growing tendency to increase the demand for energy resources, there is a need to use renewable energy sources. As noted in [1] the use of renewable energy sources can partially, and at some facilities and completely replace the use of traditional (non-renewable) energy sources. One of the most widespread sources of renewable energy is solar energy, the use of which raises the problem of predicting its arrival on the surface. The studies [2, 3] note the variability of solar energy in space, time, the complexity of modeling, and various methods are proposed for analysis taking into account the parameters of time, latitude, but on flat surfaces [2–8]. The authors in [9] proposed to use hourly data on solar radiation parameters based on open LIDAR information obtained from space satellites to accurately determine the solar radiation input to the vertical surfaces of the facades. But the authors noted the inaccuracies of the calculations in the case of difficult conditions associated with shading from neighboring objects and self-shadowing of objects with heliosystems placed on them.

The widespread use of curvilinear surfaces in modern architecture for covering large-span rooms requires solving the issues of their effective energy supply, which determines the relevance of multifactor optimization problems when integrating solar systems into them.

As noted in [10], the growing use of solar energy has led to the development of solar collectors with complex surface geometries. Conventional methods are unable to directly calculate solar radiation on such surfaces. The authors of the article [10] proposed their own method of calculations and computer code (Fortran). The method is based on a separated curved surface of a significant number of smaller planar elements to calculate the solar irradiation on each of them, at the end it is summed up to obtain the total irradiation value.

In the study [11], the authors presented a mathematical model based on the MATLAB platform for calculating the solar radiation reflected from surfaces, it passes everywhere the curved surface of the greenhouse for four days of the year.

In the article [12], the authors consider the issues of self-shadowing, which occur on solar collectors with a curved surface, which leads to an uneven distribution of solar radiation, diffuse and reflected incident solar radiation. To reduce the negative effect of self-shadowing in power generation, the authors of the study propose analytical definitions for the particular case of self-shadowing for incident solar irradiation on a common convex surface.

The study [13] examines the modeling of solar irradiation to increase the supply of solar energy to a vacuum tube collector with a parabolic concentrator using its geometric characteristics. Optical modeling is carried out by the authors by varying the angles of the solar elevation projection, and its optical efficiency is estimated by the method of mathematical modeling.

Thus, the analysis of studies represents a wide range of problems associated with modeling the input of solar irradiation for the application of heliosystems on curved surfaces. It should be noted that the problems considered in the studies are characterized by solutions to individual cases, but do not give a general idea of the process of modeling the interaction of the parameters of variable solar irradiation with the parameters of a curved surface.

In [14], the authors presented a geometric model of the distribution of solar radiation over curvilinear surfaces of enclosing structures with the ability to determine zones on it, get the maximum amount of solar radiation within a given period of time. The problem has a geometric interpretation and is reduced to finding zones on a given surface, getting the maximum amount of solar radiation within a given period of time. In [14] a geometric model of the arrival of solar radiation on the surface of the shells is described by the example of a hyperbolic paraboloid, by the example of sections of a hemisphere, by the example of an ellipsoid of revolution at a given moment in time. In work on the example of surfaces used for shaping in high-rise buildings, the mechanism of finding instant solar radiation zones on these surfaces is described. This publication is a direct continuation of the studies given in [14], in which the process of constructing an instant model of the distribution of solar radiation over the section of the coating surface was determined (a section of the surface with a family of lines of equal amount (intensity) of solar radiation applied to it).

2. Materials and Methods

The aim of this study is to develop a mechanism for the transition from an instant model of the distribution of solar radiation on the surface of the coating to an average daily distribution model. The transition from the instantaneous model to the averaged daily model in the continuous form consists in integrating the $\cos\gamma$ function at the points of the research surface Φ with respect to τ. At each exploration point, a shadow or drop check must be performed. Thus, the point-by-point determination of S_γ on the surface compartment with the subsequent tracing of isolines between the calculated surface nodes in the computational sense is simple from a discrete algorithm for finding effective solar radiation zones from the extreme position $\cos\gamma \to \min$. But analysis of various sections of surfaces, both second and higher orders (for example, a wavy surface), shows that there may be several fragments of effective solar radiation zones on the surface. In such cases, the distribution of solar radiation, taking into account the zones of intrinsic and falling shadows on the research surfaces, determines the need to apply in the general case a discrete approach, which is considered in the presented study.

For the averaged model of solar radiation per day, it is necessary to divide the daily solar trajectory into segments or fixed positions of the Sun on this trajectory and then use, instead of integration, the method of summing instantaneous intensities (the amount of solar radiation) at each calculated point. To solve this problem, it is necessary to determine the number of calculated positions of the Sun in order to obtain the correct values of solar radiation, which will arrive at each calculated point on the surface. In this case, let's consider the influx of solar radiation on curved surfaces, which most often have their own shading, which must be taken into account already at the stage of pre-design work. Let's determine the minimum arrays of calculated points on the solar trajectory for the equinox days on March 21 and September 21.09, as well as for December 21, June 22 (the days of the winter and summer solstices).

A characteristic sign of solar energy input is its dynamics, i.e. change in time, causes the main difficulties arising on the way of using the energy of sunlight and requires taking into account the factors of influence and parameters that are set. Among the factors of influence, there are those that are primary and those that are derived from them. The first should include:

– the movement of the Earth around its axis during the day (determines the change in time) and around the Sun during the year, determines the position of the axis of rotation of the Earth relative to the Sun;

– the shape and position in space of a given architectural object with a solar receiver placed on it, reflectors of sun rays, sun protection devices and neighboring shading objects, based on the tasks (azimuth, shape parameters and position of objects).

A change in the primary factors in time and space causes a change in the derivative factors that directly determine the flow of solar energy to the solar receiver in dynamics. Derived factors include:

– the direction of sunlight, set by the coordinates of the Sun (As − azimuth, Hs − height above the horizon), which change with the latitude of the area, time of day and day of the year;

– the intensity of solar energy, depends on the angle of incidence of the sun on the surface and is determined by the angle between the normal to the surface and the direction of sunlight;

– duration of exposure to direct sunlight.

These factors form the basis for effective modeling of solar systems. Finding the main parameters of solar irradiation is based on the use of the geometric model of the daily cone of solar rays, which was proposed for Insolation calculations [14]. In it, the Sun is taken as a point source, which at each moment of time gives ∞^2 a congruence of practically parallel rays. A complex of ∞^2 rays is formed per day. If to assume that during the day the Earth is in orbit at one point, then this is a complex of the 2[nd] degree. Then any point separates from this complex a daily circular cone of sunbeams, the axis of which is parallel to the axis of the Earth. It is the guide for all the sun's rays per day. The angle of inclination of the axis of the cone to the horizontal plane is equal to the latitude of the terrain. The angle φ is the angle between the axis of the cone and its generatrix, which varies throughout the year from 66°, 33′ to (180°–66°33′). The hour generators of the cone are located in the axial planes taken from noon every 15°.

The geometric model described in [5, 9, 10] is the basis for constructing a family of lines of the same level of solar radiation, both for instantaneous values of solar radiation input to the surface, and for the averaged family of lines of the same level of solar radiation. The surface model is an ordered two-dimensional point frame of sufficient freedom over a rectangular plan, and the geometric model of a set of sun rays is a cone of sun rays with apex at the irradiated point, the parameters of which for given latitude of the terrain vary depending on the season.

The amount of solar radiation (intensity) that enters the irradiated point on a given surface, at a given time S_γ, is determined by:

$$S_\gamma = S_H \cos\gamma, \quad (1)$$

where S_H − amount of solar radiation entering the site perpendicular to the direction of the sun's rays; cosγ − angle between the normal to the irradiated point of the surface and the vector opposite to the direction of the sun's rays.

Finding by (1) the amount of solar radiation S_γ at each irradiated point of the two-dimensional point frame of a given surface, let's obtain the value of the instantaneous intensity of solar radiation at the irradiated point of the frame for one fixed position of the Sun. Interpolating, let's obtain the lines corresponding to the equal value of S_γ. That is, let's obtain an instantaneous model of the distribution of solar radiation over the surface for one fixed k-th position of the Sun on the daily solar trajectory. The instantaneous value of the amount of solar radiation arriving at the point $A_{i,j}$ of a discretely given surface Φ from the k-th position of the Sun on the daily solar trajectory $(k \subset 1, N)$ (**Fig. 1**) and is determined by (1).

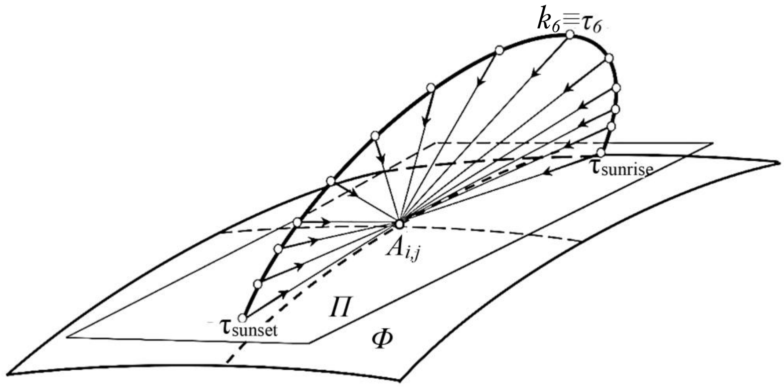


Fig. 1. Diagram of the daily solar trajectory in the interval from east ($\tau_{sunrise}$) to west (τ_{sunset}), broken down into k calculated positions of the Sun

Considering N fixed positions of the Sun during the day, let's assume that the daily intensity of solar radiation arriving at the point $A_{i,j}$ without shading is equal to the sum of N instantaneous values of the amount of solar radiation referred to the number of calculated points N on the daily solar trajectory:

$$S_\gamma^{ij} = \frac{1}{N}\sum_{k=1}^{N} S_k^{ij}. \qquad (2)$$

The resulting (2) determines the amount of solar radiation entering the point $A_{i,j}$ during the day S_γ^{ij}. Where N will determine the number of calculated points (positions) of the Sun on the daily solar trajectory.

The result of the calculation according to the proposed algorithm will be a family of lines of the same level of solar radiation during the day, which is used to analyze various options for placing the solar receiver.

In this case, it is possible to take into account two options for shading – when shading with a falling shadow and your own shadow. In the first case, an algorithm for checking the shading of a surface area by another area is used, based on the control of the number of intersections of the surface by a direct sunbeam. In the second case, the value of the cosine of the angle between the normal to the surface and the vector opposite to the direction of the sun ray is analyzed (the point is in its own shadow at $\cos \gamma < 0$). At a point on the surface that is in shadow, the $\cos\gamma$ value for a given t is assigned a zero value. In the second case, the value of the cosine of the angle between the normal to the surface and the vector opposite to the direction of the sun ray is analyzed (the point is in its own shadow at $\cos\gamma < 0$). At a point on the surface that is in shadow, the $\cos\gamma$ value for a given t is assigned a zero value.

Thus, integration is reduced to summation according to (2), and the accuracy of the solution essentially depends on the nature of the division of the solar trajectory into sections with fixed positions of the Sun and the nature of the placement of fixed positions of the Sun on the daily solar trajectory.

To determine the number of calculated fixed positions of the Sun N on the solar daily trajectory, sufficient for further calculations, let's consider the ascent of the results of calculations of the daily intensity of solar radiation at the point $A_{i,j}$ with a gradual increase in the number of fixed points on the solar trajectory in cases when their uniform and uneven placement.

3. Results

For research, consider a building with a covering in the form of a hyperbolic paraboloid with not very curved edges at latitude (δ = 52°) when located in Kyiv, Ukraine. This form of a hyperbolic paraboloid reduces the falling of a part of the surface into its own shadow, increases the amount of solar radiation to the surface. Let's take on the solar daily trajectory for June 22 the hour interval from sunrise to sunset. For the calculated day, it will be: $\tau \subset [6,22]$, that is, the Sun rises at 6:00 in the morning and sets at 22 in the evening. Let's split the solar trajectory by hours from 6 to 22 hours. Let's obtain 17 calculated positions of the Sun on the solar daily territory.

To calculate the amount of solar radiation entering the surface (1), let's use the defined in [5–7]:

$$S_H = \frac{S_o \sinh}{\sinh + C}, \tag{3}$$

$$\cos\gamma = \frac{a_x \bar{a}_x + a_y \bar{a}_y + a_z \bar{a}_z}{\sqrt{\bar{a}_x^2 + \bar{a}_y^2 + \bar{a}_z^2}\sqrt{a_x^2 + a_y^2 + a_z^2}}, \tag{4}$$

where S_o – solar constant equal to 1353 W/m² (1940 cal/(cm²×min) or 4871 kJ/m²·h – solstice height; C – coefficient characterizing the transparency of the atmosphere, $\bar{a}_x \bar{a}_y \bar{a}_z a_x a_y a_z$ – cosines of the vector, the reverse direction of the sun's rays and the direction cosines of the normal.

Substituting the values obtained from (3), (4) into (1) and performing the appropriate calculations, let's find the amount of solar radiation arriving at one calculated point on the surface from 17 positions of the Sun on the solar trajectory. Substituting the values obtained from (3), (4) into (1) and performing the appropriate calculations, let's find the amount of solar radiation arriving at one calculated point on the surface from 17 positions of the Sun on the solar trajectory. That is, let's obtain 17 instantaneous values of the amount of solar radiation at one calculated point $A_{i,j}$, fences for the calculated period of time, adding them let's obtain the average daily value of the amount of solar radiation at the calculated point $A_{i,j}$, fences. Interpolating and tracing the isolines between the calculated points on a given surface Φ, let's obtain on this surface isolines that correspond to the amount of solar radiation equal to the calculated day S_γ. That is, let's obtain an average daily model of the intensity of solar radiation on a given surface Φ. Hence, it is possible to conclude that let's obtain the average daily model as a summation of instantaneous models of solar radiation intensity on a given surface Φ, which will be correct for other fixed positions of the Sun on the solar trajectory.

Through the quantitative values of solar radiation arriving at the design point of the surface, with the most uneven or uniform split of the solar trajectory, let's determine the correct values of the number of solar trajectory partitions for different values of the declination angle of the Sun (for March 21 and September 21, as well as for December 21). To do this, let's take the maximum number of partitions (17 fixed positions of the Sun) for June 22 at the latitude of Kyiv and perform the appropriate calculations. Let's summarize the calculation data in **Table 1**. To do this, let's take the maximum number of partitions (17 fixed positions of the Sun) for June 22 at the latitude of Kyiv and perform the appropriate calculations. Let's summarize the calculation data in **Table 1**.

Similarly, let's perform calculations at the latitude of Kyiv (δ = 52°), for March 21 and September 21, as well as for December 21. Let's construct diagrams of differences of the daily amount of solar radiation for both uniform and non-uniform breakdown of the positions of the Sun on the daily solar trajectory $(\tau \subset [6,22])$ for June 22, September 21, December 21, March 21 (**Fig. 2**).

Considering the graphs of the differences in the amount of solar radiation entering the calculated point of the surface with the most uneven or the most uniform breakdown of the solar daily trajectory by fixed positions of the Sun, for the latitude of m. Kyiv, it is possible to draw the following conclusions:

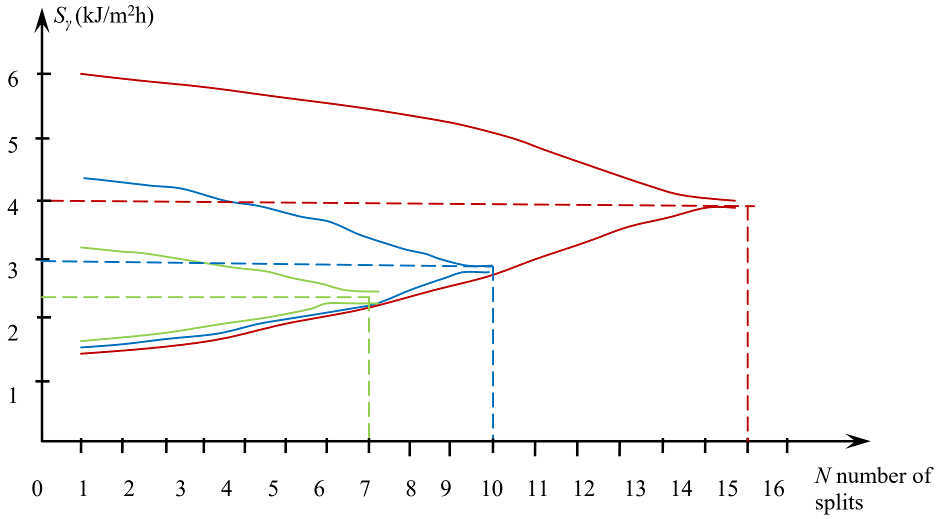
– for June 22 the most correct will be 17 fixed positions of the Sun on the diurnal trajectory;

– for June 22 the most correct will be 8 fixed positions of the Sun on the diurnal trajectory;

– for September 21and September 21the most correct will be 11 fixed positions of the Sun on the diurnal trajectory.

Table 1
Determination of the optimal number of partitions of the solar trajectory for June 22 at the latitude of Kyiv, Ukraine

Number of splits	Splits of the positions of the Sun on the daily solar trajectory at latitude (δ = 52°)			
	maximum uneven		maximum even	
	Splits of the trajectory into fixed positions of the Sun (hours of the day)	The amount of solar radiation (kJ/m^2·h)	Splits of the trajectory into fixed positions of the Sun (hours of the day)	The amount of solar radiation (kJ/m^2·h)
1	6	0.993	14	5.97
2	6, 22	0.993	14, 15	5.725
3	6, 22, 21	1.26	13, 14, 15	5.61
4	6, 7, 22, 21	1.39	13, 14, 15, 16	5.53
5	6, 7, 8, 22, 21	1.64	12, 13, 14, 15, 16	5.48
6	6, 7, 8, 22, 21, 20	1.81	12–17	5.374
7	6, 7, 8, 9, 22, 21, 20	2.05	11–17	5.298
8	6, 7, 8, 9, 22, 21, 20, 19	2.23	11–18	5.16
9	6, 7, 8, 9, 10, 22, 21, 20, 19	2.45	10–18	5.05
10	6, 7, 8, 9, 10, 22, 21, 20, 19, 18	2.625	10–19	4.9
11	6, 7, 8, 9, 10, 11, 22, 21, 20, 19, 18	2.82	9–12	4.77
12	6, 7, 8, 9, 10, 11, 22, 21, 20, 19, 18, 17	2.99	9–20	4.59
13	6, 7, 8, 9, 10, 11, 12, 22, 21, 20, 19, 18, 17	3.17	8–20	4.44
14	6, 7, 8, 9, 10, 11, 12, 22, 21, 20, 19, 18, 17, 16	3.32	8–21	4.26
15	6, 7, 8, 9, 10, 11, 12, 13, 22, 21, 20, 19, 18, 17, 16	3.47	7–21	4.09
16	6–13, 15–22	3.06	7–22	3.89
17	6–22	3.725	6–22	3.725



1– graph of convergence of solar radiation values on 22.06
2 – also March 21 and September 21
3 – also December 21

Fig. 2. Diagrams of differences of the daily amount of solar radiation for both uniform and non-uniform breakdown of the positions of the Sun on the daily solar trajectory for June 22, September 21, December 21, March 21

As can be seen from the graphs (**Fig. 2**), with an increase in the calculated points N, the value of the daily solar intensity at a given point S_γ^{ij} asymptotically approaches a certain value S_{γ}^{ij} which at $N \to \infty$ and will be integral. From the graph it is possible to that with different declination of the solar trajectory, or the number of partitions on the trajectories will be different. For low latitudes, it will decrease, and for high latitudes, it will increase. For the equator, the number of partitions on the solar trajectory is $N = 25$.

4. Discussion

Research analysis shows the development of efficient means of using solar energy as a source of renewable energy in buildings. At the same time, to a greater extent, the research concerns the calculation of the values of the total solar radiation for the use of heliosystems on horizontal and vertical planes [4, 5, 9], without the possibility of effective modeling of the arrival of solar radiation in a building with a curved surface. It should be noted that the problems considered in the studies [10–13] are characterized by solutions to individual cases, but do not give a general idea of the process of modeling the interaction of the parameters of variable solar irradiation with the parameters of a curved surface.

The aim of the presented study is to develop tools for modeling the distribution of solar radiation on curvilinear surfaces for the effective location of solar thermal devices on them. The study solves the problem of developing a mechanism for the transition from an instantaneous model of the distribution of solar radiation to an average daily model in the form of a family of lines of the same level of solar radiation on a certain curved surface during the day. The optimal number of fixed positions of the Sun on a solar trajectory for various angles of declination of the Sun has been determined (for June 22 $N = 17$, for September 21, March 21 $N = 11$, for December 21 $N = 8$), does not depend on the maximally uniform or maximally uneven position of the fixed positions of the Sun on the solar trajectory. The research results are based on the representation of the process of interaction between the parameters of variable sunlight and the geometric parameters of the shape of a curved surface. The results of this study are presented in **Table 1** and in **Fig. 2.** In the course of the research, an example of modeling the amount of solar radiation entering the surface of a hyperbolic paraboloid during the day is shown.

The next development of this study will be the transition to averaged annual models of the distribution of solar radiation over curved surfaces. For calculations of the year-round use of the solar system, it is advisable to choose a day that will be averaged for the year. Considering the given disagreement graphs in **Fig. 2**, for such a day, it is possible to take the day of the equinox (it occurs twice a year on March 21 and September 21), determined by 11 fixed positions of the Sun in the sky. But it should be noted that such a simplification is correct only for simple scenes, since a fixed year-round averaging direction under complex conditions of mutual shading cannot give an accurate picture of the distribution of solar radiation.

5. Conclusions

Along with studies of quantitative geometric characteristics and differential properties of many parametric ruled sets (order and class of congruences, degree of a complex), the question of their qualitative analysis remains open. The qualitative characteristics of sets of lines should be understood as such issues as the density of rays of ruled sets of some uniformity passing through a given plane or at a given point. As well as the presence and characteristics of such a regular type of surfaces with an extreme, or predetermined number of elements of the ruled set, intersects this type of surfaces. Or the nature of the bundle of a ruled set with a given density distribution. The full qualitative analysis of ruled sets is not exclusively the prerogative of synthetic methods; research also tends to the complex application of integral-differential approaches and computer modeling. These characteristics are of practical use. An in-depth study of the qualitative characteristics of various ruled sets is one of the directions for further research.

For example, the concept of density is associated with the energy parameters of the process under study. In particular, it allows to determine the size of the effective solar radiation zone. The representation of the process of interaction between the parameters of alternating sunlight proposed in the study (based on the geometric model of the diurnal cone of solar rays [14]) and the geometric parameters of the shape of a curved surface forms the basis of the discrete approach considered in the present study. The result of the calculation according to the proposed algorithm is presented as a family of lines of the same level of solar radiation during the day (for June 21) on the surface of a hyperbolic paraboloid at a latitude (δ = 52°) located in Kyiv, Ukraine, which is used to analyze options for placing solar receivers. Based on the analysis of similarly performed calculations, at the latitude of Kyiv (δ = 52), the optimal number of fixed positions of the Sun on the solar trajectory for different angles of solar declination was determined (for June 22 $N = 17$, for September 21, March 21 $N = 11$, for 2 = 8), which forms the basis for further determination of the averaged daily model (with a value of $N = 11$). Summing up, let's note that using the values of the averaged daily model, it is possible to proceed to obtaining averaged daily models for the estimated time interval at the stage of pre-project proposals to predict the efficiency of using the solar system (knowing the amount of solar radiation entering the surface).

It should be noted that studies of the problems of integrating solar systems onto curved surfaces of buildings require further development, and the proposed modeling algorithm can form the basis for further research.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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