## SOLAR RADIATION AND FORECASTING

# Analysis of Data on the Resource of Solar Energy for a Set Geographic Point

**Yu. V. Daus[a], \*, I. V. Yudaev[a], S. A. Tarasov[b], and V. V. Kharchenko[c]**

*[a] St. Petersburg State Agrarian University, St. Petersburg, 196601 Russia*
*[b] St. Petersburg Electrotechnical University LETI, St. Petersburg, 197022 Russia*
*[c] Federal Scientific Agroengineering Center VIM, Moscow, 109428 Russia*
*\*e-mail: zirochka2505@gmail.com*

**Abstract**—The information on the various parameters of solar radiation should be sufficient, relevant, accessible from the point of view of design, optimization, and justification of the parameters of photovoltaic installations in the place of its proposed location. However, in spite of the large number of sources of actinometrical information, certain difficulties arise when conducting solar engineering calculations associated with database limitations, the large distance from the considered geographical point, or the laboriousness of the research that are needed to be carried out. The purpose of the study is to analyze the available data on the solar energy resource for a set geographic point (46.8° N, 40.6 E), obtained by the indirect method for assessing the parameters of solar radiation using data from ground-based metrological stations; indirect method for assessing the parameters of solar radiation using satellite measurements; calculated method for determining the intensity of solar radiation; and experimental study of the characteristics of solar radiation. The analysis showed that not all approaches provide data on the direct and diffused components of solar radiation. In addition, the availability of hourly values of solar radiation is very important, because only they make it possible to predict the mode of operation of a photovoltaic installation and coordinate its mode of operation with the load schedule of the consumer. The deviation between the data of various sources of actinometrical information can reach 53.0% for hourly values, 58.1% for daily values, 43.1% for monthly values, and 39.1% for annual values, and can significantly affect solar engineer calculations for the choice of parameters of the photovoltaic installation equipment or make great adjustments to the issues of justifying the economic efficiency and feasibility of photovoltaic installation application.

## INTRODUCTION

When solving problems related to the power supply of the consumer by means of photovoltaic installations [1–5], the issue of the availability of data on solar radiation is important. The amount of information about various parameters of solar radiation should be sufficient, relevant, and accessible from the point of view of designing, optimizing, and justifying the parameters of photovoltaic installations and consumer requirements at a given geographical point [6].

The most obvious way to obtain actinometric information for the geographical point under consideration is to conduct an experimental study. However, this method requires a long observation period and high costs for measuring equipment, maintenance, and calibration of instruments [7]. In addition, monitoring the intensity of solar radiation over 1 year provides a data set that can be used to check the applicability of other approaches to determining the resource of solar energy, but which is not sufficient for the

selection and evaluation of the parameters of a photovoltaic installation, since the solar radiation flux coming to receiving surface is a variable value and depends on many factors.

The lack of information about the resource of solar energy at a given geographical point has led to the development of two main directions in determining the parameters of solar radiation: indirect methods for processing statistical data (empirical models [8], machine learning methods [9], satellite remote sensing methods [10]) and calculation methods [11]. The data obtained by ground-based meteorological stations and satellite measurements are used as initial data in indirect methods for estimating solar radiation parameters.

The main problem of functioning and data collection at meteorological stations is the high price of equipment, the complexity of its maintenance, the large amount of stored data, low branching, and density of stations. Such heterogeneity leads to the fact

that entire regions remain uncovered, especially territories with complex topography [12]. Satellite measurement data are available for different periods, in different areas of the globe with a variety of grid resolutions. However, despite the wide geographical coverage, this method is less accurate than ground-based measurements, since monitoring is carried out in the extra-atmospheric region, taking into account the processes occurring in the atmosphere, the state of cloudiness, the composition of gases, and the effect on the processes of solar radiation scattering occurring in the atmosphere based on the radiation balance and is characterized by a higher systematic error [13].

The analysis of data presented by statistically significant arrays of satellite and ground-based measurements is widely presented in [14, 15]. The article analyzes the accuracy of forecasting the energy characteristics of photovoltaic systems using various climate databases (NASA POWER, SARAH-E, CLARA-A, ERA5, Meteonorm, etc.) on the example of several geographical points by comparing with calculations based on data from the World Radiation Data Centre (WRDC). The authors note that the data presented in these databases provide a spread in the forecast error of the required nominal power of solar panels at the level from 10−20% to several hundred percent. Paper [16] presents the results of evaluation studies of an unprecedented scale on eight gridded remote sensing bases, including six satellite systems (CAMS-RAD, NSRDB, SARAH-2, SARAH-E, CERES-SYN1deg, and Solcast) and two systems based on reanalysis (ERA5 and MERRA-2 used in baseline data for 27 years). It is noted that approaches to predicting the intensity of solar radiation are becoming more and more complex, so it is recommended to perform verification throughout the entire process of making forecasts [25].

Calculation methods for determining the characteristics of solar radiation on a horizontal surface, taking into account the direct component of insolation and atmospheric conditions are widely presented in scientific literature [11, 15, 17−19]. However, with all the variety of computational approaches to determining the intensity of solar radiation, all methods require verification of the results when conducting solar calculations according to the database of long-term observations at the proposed location of the photovoltaic installation. Verification is most often associated with labor-intensive calculations, so in the literature one can find methods for calculating the potential of solar energy at a given geographical point, which are based on a combination of calculation methods and data from real meteorological observations, implemented in the form of ready-made algorithms and programs [20, 21].

Thus, despite the large number of sources of actinometric information, when performing solar engineering calculations, certain difficulties arise due to the limited databases the great distance from the geographical point under consideration, or the laboriousness of the surveys. The choice of the source of actinometric information determines in the future the choice of the method for calculating the parameters of photovoltaic installations, namely, the method of matching the generation modes and the mode of consumption of electric energy and the choice of the type and parameters of backup and storage devices.

## RESEARCH METHOD

The purpose of the study is to analyze the available data obtained from various sources of actinometric information on the resource of solar energy on a horizontal surface for a given geographical point.

Consider the example of the city of Zernograd, Rostov oblast (geographical coordinates: 46.8° N, 40.6° E) what data and to what extent are available and we will conduct their comparative analysis.

For the geographical point under consideration, data on the intensity of solar radiation can be obtained from the following sources:

1. Indirect method for estimating solar radiation parameters using data from ground-based meteorological stations (Indirect-1). Handbook on the intensity of solar radiation [22]. In the climate reference book, data are presented for the city of Rostov-on-Don and the village of Gigant in the Salsky district, which are located at a distance of 62 and 88 km at the points with coordinates: 47.2° N, 39.7° E and 46.5° N and 41.3° E, respectively. The reference manual provides monthly and hourly (with an interval of three h) for the village of Gigant and sums of total solar radiation on a horizontal surface and annual and daily by months for the city of Rostov-on-Don. Reference data are obtained for average cloudy conditions.

2. An indirect method for estimating solar radiation parameters using satellite measurements. The NASA POWER database [23] (Indirect-2) contains an array of data obtained as a result of satellite measurements in the initial spatial resolution of monitoring [23]. When querying in the specified database, data is displayed for a point with coordinates 47° N and 40.5° E, which is located at a distance of 25 km from the considered point (Zernograd). The following data from the NASA POWER database were used: daily, monthly, and annual sums of total solar radiation averaged over 22 years on a horizontal surface with the possibility of choosing a geographic point.

3. Calculation method for determining the intensity of solar radiation. A computer program [24] for calculating the estimate of the potential of solar energy at a given geographic point with the required spatial orientation in remote areas of the Southern Federal District, which is based on a combination of an analytical approach (according to the Byrd method) and satellite meteorological observations (NASA POWER)

[23]. This program allows one to calculate the hourly, daily, monthly, and annual sums of direct, scattered, reflected, and total solar radiation to a receiving surface differently oriented in space according to the method [25].

4. Experimental study of the characteristics of solar radiation. Monitoring of solar insolation using the research complex consists of: control photovoltaic cell *1*; photovoltaic module *2* (*P*max = 5 W, *U*mp = 9 V); electronic goniometer *3*; multimeters *4* and *5*; laboratory resistance box *6* (accuracy class 0.1); and swivel-tilt mechanism *7*, which is a movable base for adjusting its angle in space.

The determination of the output power of the photovoltaic module was carried out in natural sunlight on a site not shaded by building structures and green spaces according to [26] at a point with geographic coordinates 46.8° N, 40.3° E (Zernograd).

## RESULTS AND DISCUSSION

Table 1 presents data on the availability and composition of data for each source of actinometric information.

As can be seen from Table 1, not all sources of actinometric information can provide a complete array of data for further solar engineering calculations and significantly affect the choice of further calculation methods for substantiating the parameters of photovoltaic installations. All methods for estimating incoming solar study contain data for a horizontal area (conversion to an inclined plane can be done in the NASA POWER system and by calculation). In addition, not all approaches to the determination of inso-
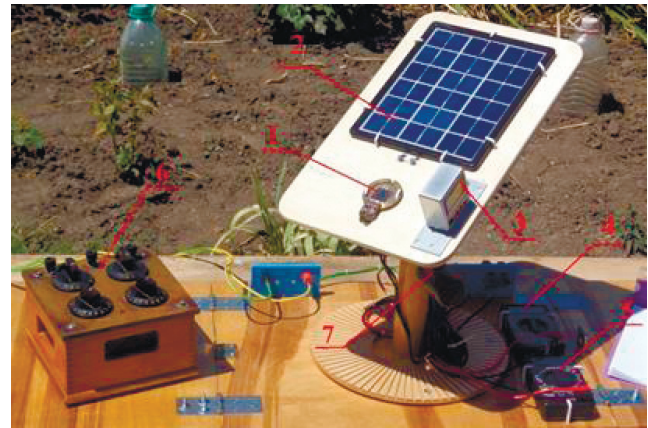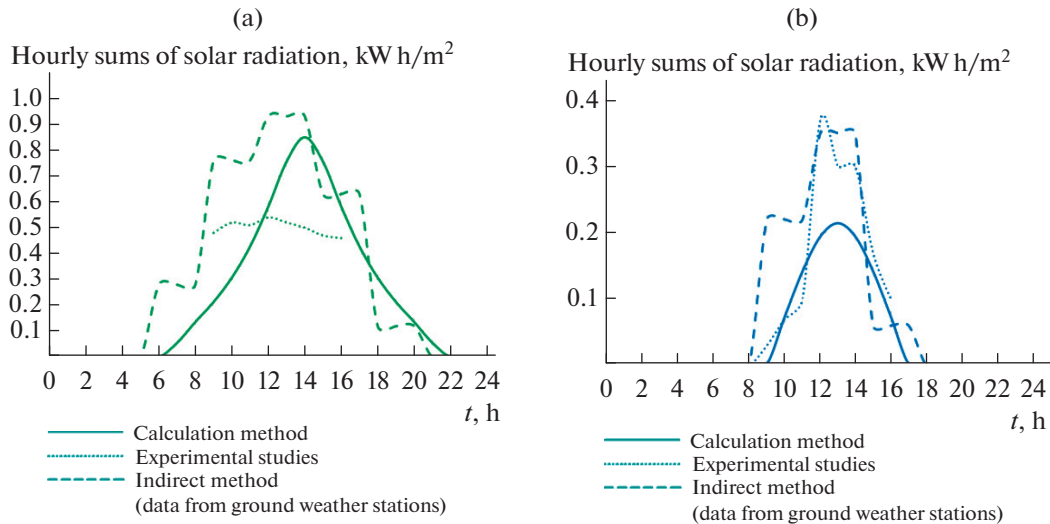


**Fig. 1.** Photo of research complex.

lation provide data on the direct and diffuse components of solar radiation, which is also necessary for solar engineering calculations. It is also very important to have complete information about the hourly values of solar radiation.

Figure 2 shows daily graphs of the arrival of solar radiation on a horizontal receiving surface for 2 characteristic days of the year: June 22 and December 22 for various sources of actinometric information.

The curves of the hourly sums of solar radiation for the calculation method for the summer and winter characteristic days have a maximum solar radiation intensity at 14:00 and 13:00, respectively. According to the Indirect-2 method data averaged over 20 years of observations the maximum insolation on June 22 is expected from 12:00 up to 14:00, and it is 9.3% higher

**Table 1.** Composition and characteristics of actinometrical information on solar radiation obtained from various sources for a given geographic point

| | Indirect-1 [22] | Indirect-2 [23] | Calculation method [24] | Experimental study |
|---|---|---|---|---|
| Injection, ° | 0°, optimal | 0° | 0°–360° | 0°–360° |
| Orientation,° | – | – | 0°–360° | 0°–360° |
| Geographical point, km from the point | 88 km | 111 km for radiation data 60 km for metrological data | 25 km | – |
| Observation period | 1965–1980 | from 1985 to present | 1985–2015 | 2019 |
| Total: | | | | |
| — sentries | + | + | + | From 08:00 to 17:00 |
| — daily allowance | + | + | + | From 08:00 to 17:00 |
| — period | + | + | + | Characteristic days |
| — annual | + | + | + | Characteristic days |
| Components of radiation: | | | | |
| — total | + | + | + | + |
| — straight | + | + | + | – |
| — scattered | + | + | + | – |
| — reflected | – | + | + | – |

(a)

Hourly sums of solar radiation, kW h/m$^2$



(b)

Hourly sums of solar radiation, kW h/m$^2$



**Fig. 2.** Hourly sums of solar radiation obtained from various sources of actinometric information for two characteristic days: June 22 (a) and December 22 (b).

than for the calculation method. At the same time, an experimental study for June 22, 2020 (a cloudy day according to the weather archive) revealed a fairly uniform level of incoming solar radiation flux on a horizontal surface from 8:00 up to 16:00 of 0.49–0.58 kW h, with a maximum at 12:00. In the morning from 08:00 to 01:00, the intensity of solar radiation according to the calculation method is 0.15–0.3 kW h, the indirect method is 0.31–0.8 kW h, and the experimental study is 0.51–0.56 kW h. The graphs of the hourly sums of solar radiation on a horizontal surface for the indirect and calculation methods are the closest, which is due to the long period of actinometric observations on which they are based, 20 and 25 years, respectively. The stepwise nature of the hourly sums of solar radiation for experimental and ground-based monitoring is due to the change in the incoming solar radiation flux to Earth's surface during changes in the atmosphere, the state of which is dynamic.

The winter day (December 22, 2021), when the experimental study was carried out, turned out to be sunny and clear from 11:00 up to 16:00, this explains the high level of solar radiation intensity. The maximum for all three sources of actinometric information occurs at about the same time, from 12:00 up to 14:00, the observed irregularities are due to instantaneous changes in the state of the atmosphere. The value of the peaks of the incoming solar radiation flux for the Indirect 1 and experimental methods are almost equal (the deviation does not exceed 5%), and the calculation method is characterized by the level of insolation significantly lower at noon (by 53%). At 10:00, the solar radiation intensity is 0.08 kW h for the calculated and experimental methods and 0.23 kW h for the Indirect-1 method. At 16:00 the flux of solar radiation is 0.06 kW h for the calculated and experimental meth-

ods and 0.10 kW h for the Indirect-1 method. This difference between the indirect method (ground meteorological stations) and the calculation method is due to the fact that the latter also uses data from an indirect method based on satellite measurements and satellite measurements do not reflect as closely the influence of atmospheric conditions during the day and, despite verification with ground-based data, are carried out in the extra-atmospheric region, taking into account the processes occurring in the atmosphere, the state of cloudiness and gas composition, and the effect of reflected solar radiation on processes occurring in the atmospheric layer.

Figure 3 shows daily sums for four characteristic days of the year on March 23, June 22, September 23, and December 22.

It can be seen from Fig. 3 that for the winter day the data of the indirect method (satellite measurements), the experimental study, and the calculation method are the closest in terms of values (deviation 4%), while for the Indirect-1 method the deviation is 47%. For typical summer and autumn days, the regularities of the relative change in the daily sums of solar radiation according to different approaches to the determination of actinometric information are the same: the calculation method and Indirect-2 are closest in value to each other; the deviation from the above (calculated and Indirect-2) for the experimental study is 29–35%, which is due to the short observation period (1 year) for the experiment. The excess of insolation values for the Indirect-1 method by 29–39% compared to the calculated method may be due to the different method and location of the initial actinometric measurements. On a spring day, the deviation between the values of the daily intensity of solar radiation obtained by the Indirect-1 method and the experimental study from

Daily sums of solar radiation, kW h/(m$^2$ day)
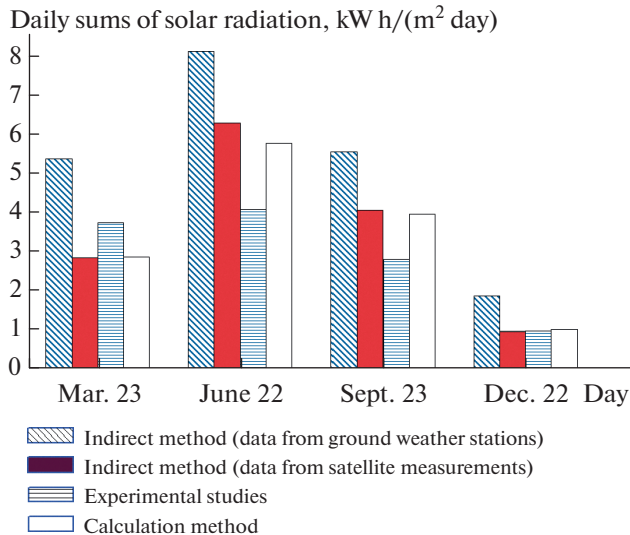


**Fig. 3.** Daily sums of solar radiation from various sources of actinometrical information for four characteristic days of a year.

Monthly sums of solar radiation, kW h/(m$^2$ month)
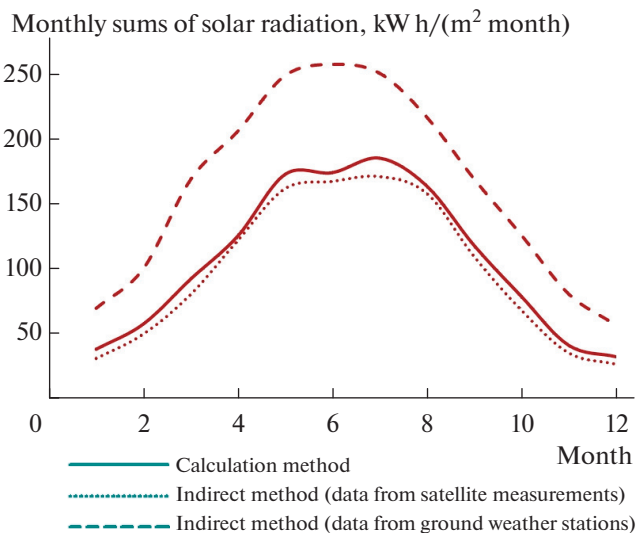


**Fig. 4.** Monthly values of solar radiation obtained from various sources of actinometrical information.

the values obtained by the calculation method is 5% and 58%, respectively. A slight deviation between the data on the intensity of solar radiation obtained by the calculation method and the Indirect-2 method is due to the fact that the values are corrected according to the average monthly data from the NASA POWER database.

Figure 4 presents the monthly sums of solar insolation obtained from various sources of actinometric information.

Deviation of monthly amounts of solar insolation are lowest for the calculated and Indirect-2 methods:

from 1–5% in the spring–summer period and up to 32–38% in the winter period. The difference between the data of the Indirect-1 method is already significant: the deviation ranges from 32–43% for the summer period to 72.7–89% in the winter.

The annual amount of incoming total solar radiation is 1955 kW h/m$^2$ according to the Indirect-1 method, 1186 kW h/m$^2$ according to the Indirect-2 method, and 1284 kW h/m$^2$ according to the calculation method. Such a deviation can reach 39%, and significantly affect the choice of parameters for the equipment of a photovoltaic installation in solar engineering calculations or make significant adjustments to the justification of economic efficiency and the feasibility of its use.

## CONCLUSIONS

Despite the large number of sources of actinometric information, there are difficulties in carrying out solar engineering calculations due to the limited databases, a large distance from a geographical point, or the complexity of the surveys. The choice of the source of actinometric information determines the choice of the method for calculating the parameters of photovoltaic installations (the method of matching the modes of generation and the mode of consumption of electric energy, the choice of the type and parameters of backup and storage devices). The analysis of the available data obtained from various sources of actinometric information on the resource of solar energy on a horizontal surface was carried out using the example of the city of Zernograd (geographical coordinates: 46.8° N, 40.6° E). For the point under consideration, data on solar radiation were obtained from the following sources: indirect method using data from ground meteorological stations; indirect method using satellite measurement data; calculation method for determining the intensity of solar radiation; and experimental study of the characteristics of solar radiation.

The analysis showed that not all sources of actinometric information can provide the necessary array of data for solar engineering calculations, which may affect the choice of substantiation of the parameters of photovoltaic installations. All methods for estimating incoming solar learning contain data for a horizontal area. In addition, not all approaches to the determination of solar insolation provide data on the direct and diffuse components of solar radiation, which is also necessary for solar engineering calculations. It is also important to have complete information about the hourly values of solar radiation, which makes it possible to predict the mode of a photovoltaic installation.

The deviation between the data of various sources of actinometric information can reach 53% for hourly sums, 4–58% for daily sums, 1–43% for monthly sums, and 39% for annual sums, and significantly affect the solar engineering calculations of the param-

eters of a photovoltaic installation or make adjustments to the issues of substantiating the economic efficiency and expediency of application.

## ACKNOWLEDGMENTS

## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

## REFERENCES

1. Panchenko, V.A., Solar roof panels for electric and thermal generation, *Appl. Sol. Energy,* 2018, vol. 54, no. 5, pp. 350−353.

2. Kharchenko, V., Nikitin, B., Tikhonov, P., Panchenko, V., and Vasant, P., Evaluation of the silicon solar cell parameters, *Adv. Intell. Syst. Comput.,* 2019, vol. 866, pp. 328−336.

3. Panchenko, V., Photovoltaic solar modules for autonomous heat and power supply, *IOP Conference Series: Earth and Environmental Science,* 2019, vol. 317, no. 1, id. 012002.

4. Lamkin, I.A., Tarasov, S.A., Petrov, A.A., Menkovich, E.A., Solomonov, A.V., and Kurin, S.Yu., Research of the solar-blind and visible-blind photodetectors, based on the AlGaN solid solutions, *J. Phys.: Conf. Ser.,* 2014, vol. 572, no. 1, id. 012063.

5. Kurin, S.Yu., Antipov, A.A., Roenkov, A.D., Barash, I.S., Helava, H.I., Menkovich, E.A., Tarasov, S.A., Lamkin, I.A., Shmidt, N.M., and Makarov, Yu.N., UV LEDs for high-current operation, *J. Phys.: Conf. Ser.,* 2013, vol. 461, no. 1, id. 012028.

6. Lee, K., Yoo, H., and Levermore, G.J., Quality control and estimation hourly solar irradiation on inclined surfaces in South Korea, *Renewable Energy,* 2013, vol. 57, pp. 190−199.

7. Muzathik, A.M., Ibrahim, M.Z., Samo, K.B., and Nik, W.B.W., Estimation of global solar irradiation on horizontal and inclined surfaces based on the horizontal measurements, *Energy,* 2011, vol. 36, no. 2, pp. 812−818.

8. Angstrom, A., Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation, *Meteorol. Soc.,* 1924, vol. 50, pp. 121−125.

9. Kaba, K., Sarıgül, M., Avcı, M., and Kandırmaz, H.M., Estimation of daily global solar radiation using deep learning model, *Energy,* 2018, vol. 162, pp. 126−135.

10. Tang, W.J., Li, J., Yang, K., Qin, J., Zhang, G.Q., and Wang, Y., Dependence accuracy of global horizontal irradiance at different scales on satellite sampling frequency, *Sol. Energy,* 2019, vol. 193, pp. 597−603.

11. Ayvazoğluyüksel Özge and Filik Ümmühan Başaran, Estimation methods of global solar radiation, cell temperature and solar power forecasting: A review and case study in Eskisehir, *Renewable Sustainable Energy Rev.,* 2018, vol. 91, pp. 639−653.

12. Angelis-Dimakis, A., Biberacher, M., Dominguez, J., Fiorese, G., Gadocha, S., Gnansounou, E., Guariso, G., Kartalidis, A., Panichelli, L., Pinedo, I., and Robba, M., Methods and tools to evaluate the availability of renewable energy sources, *Renewable Sustainable Energy Rev.,* 2011, vol. 15, pp. 1182−1200.

13. Tourasse, G. and Dumortier, D., Development of a system measuring the solar radiation spectrum in 5 planes for daylight and PV applications, *Energy Procedia,* 2014, vol. 57, pp. 1110−1119.

14. Frid, S.E., Lisitskaya, N.V., and Popel, O.S., Results of analysis of the applicability of satellite observations and reanalysis data for simulations of autonomous solar power systems, *Dokl. Phys.,* 2019, vol. 64, pp. 381−383.

15. Liu, B.Y.H. and Jordan, R.C., The interrelationship and characteristic distribution of direct, diffuse and total solar radiation, *Sol. Energy,* 1960, no. 4 (3), pp. 1−19.

16. Fortov, V.E. and Popel', O.S., The current status of the development of renewable energy sources worldwide and in Russia, *Therm. Eng.,* 2014, vol. 61, no. 6, pp. 389−398.

17. Newell, T.A., Simple models for hourly to daily radiation ratio correlations, *Sol. Energy,* 1983, vol. 31, no. 3, pp. 339−342.

18. Jain, P.C., Comparison of techniques for the estimation of daily global irradiation and a new technique for the estimation of hourly global irradiation, *Sol. Wind Technol.,* 1984, no. 1 (2), pp. 123−134.

19. Jain, P.C., Estimation of monthly average hourly global and diffuse irradiation, *Sol. Wind Technol.,* 1988, no. 5, pp. 7−14.

20. Daus, J., Desyatnichenko, D., and Stepanchuk, G., Analysis of approaches to determining solar radiation intensity at preset geographical point, *Proc. 2020 Int. Conf. on Industrial Engineering, Applications and Manufacturing,* 2020, id. 9111932.

21. Daus, Y.V., Pavlov, K.A., Yudaev, I.V., and Dyachenko, V.V., Increasing solar radiation flux on the surface of flat-plate solar power plants in Kamchatka krai conditions, *Appl. Sol. Energy,* 2019, vol. 55, no. 2, pp. 101−105.

22. *Nauchno-prikladnoi spravochnik po klimatu SSSR: Volgogradskaya, Rostovskaya i Astrakhanskaya oblasti, Krasnodarskii i Stavropol'skii krai, Kalmytskaya, Kabardino-Balkarskaya, Checheno-Ingushskaya i Severo-Osetinskaya respublika* (Scientific and Applied Reference Book on the Climate of the USSR: Volgograd, Rostov, and Astrakhan Oblasts, Krasnodar, and Stavropol Krais, Kalmyk, Kabardino-Balkarian, Chechen-Ingush, and North Ossetian Republics), Leningrad: Gidrometeoizdat, 1990, ser. 3, parts 1−6, iss. 13.

23. Surface Meteorology and Solar Energy. https://power.larc.nasa.gov/. Accessed February 1, 2021.

24. Daus, Yu.V., Kharchenko, V.V., and Yudaev, I.V., Evaluation of solar radiation intensity for the territory of the Southern Federal District of Russia when designing microgrids based on renewable energy sources, *Appl. Sol. Energy,* 2016, vol. 52, no. 2, pp. 124−129.

25. Yanga, D. and Bright, J.M., Worldwide validation of 8 satellite-derived and reanalysis solar radiation products: A preliminary evaluation and overall metrics for hourly data over 27 years, *Sol. Energy,* 2020, vol. 210, pp. 3−19.

26. *GOST* (State Standard) *28977-91 (MEK 904-1-87): Photovoltaic Devices. Part 1: Photovoltaic Current−Voltage Measurements,* 2004.