POSSIBILITIES OF SOLAR ENERGY APPLICATION IN RUSSIAN CITIES

by

Zhanna MINGALEVA [a*] ***and Natalia SHPAK*** [b]

[a] Perm National Research Polytechnic University, Perm, Russia
[b] Ural Federal University, Yekaterinburg, Russia

Original scientific paper
DOI: 10.2298/TSCI150330087M

The possibilities of solar energy application in the biggest Russian cities are studied and analyzed. The main research goal is to investigate the possibility of solar energy technical use in Russian regions. The research method is based on the calculation of the territory power capacity and its sufficiency for solar power engineering development. The authors have carried out the analysis of total solar radiation falling on the horizontal and inclined surfaces within an astronomical year. The basis of the data using spatial statistics of solar radiation inflow in different seasons during the annual cycle. The assessment of solar radiation sufficiency by "technically accepted" criterion is made on the basis of Veynberg criteria. The authors conclude that the effectiveness of the solar energy production development is the most appropriate in the city of Vladivostok and obviously, it is not prospective in the authors' places of residence, such as Perm and Sverdlovsk Regions.

Key words: *solar energy, alternative energy, source of energy, energy storage, energy efficiency*

Introduction

In many countries solar radiation is widely used as an alternative source of energy, the so-called solar energy [1-4]. The main characteristic to identify opportunities for the development of solar energy is the measure of the solar energy amount falling on the surface of the solar absorber, tilted at a certain angle. On this basis, taking into account physical characteristics of the solar absorber is determined by the possible specific annual energy production of the solar installation. This figure is the starting point for determining the technical potential of solar energy production in a particular area and determines the application and effectiveness of solar energy development in specific areas. The main limitations associated with the use of solar energy due to its impermanence are that solar installations do not work at night and are ineffective in cloudy weather. For regions in the northern latitudes, which are the analyzed areas, they are important seasonal differences in day length.

Method

As the main method of the power potential assessment of solar power engineering technologies (technique) a geostatistical analysis and geographic information system (GIS) are applied to various territories in the world [5, 6].

* Corresponding author; e-mail: mingal1@pstu.ru

As statistical base of the calculations these geostatistical analysis and GIS are received by the scientists from the Perm State National Research University for the territory of Perm city and the table of insolations of the various territories of Russia [7, 8]. Also, as the initial base for calculations, other methods of modern authors were taken [9-12]. The calculation technique presented in the report, which is used for the assessment of the regional climate change features of willows regions of Russia and Belarus, was prepared in 2007 by the scientists of the main geophysical observatory named after Voyeykov [10].

For the comparison, there were chosen some cities of the South of Russia, some of the central part and some northern located and the territories approaching them. We will remind that the Arctic Circle is in 66°33'44" (66.5622°) to the north from the equator, so the part of the territories of the analyzed regions, including Perm Region, are near the Arctic Circle. Range of the cities taken into the research from the south to the north, is given in tab.1.

For the definition of the territory development possibility in solar power the engineering criteria of Veynberg were used [13, 14]. According to Veynberg criteria, solar radiation can be considered *technically accepted* when its intensity (S) reaches 0.42 kW/m^2. Respectively, complying with this size, the power capacity of the territory is considered sufficient for the development of solar power engineering. The cases of the excess of these indicators point to the existence of power security of these territories, and their smaller values – to the lack of the power security of certain territories.

For the determination of the power capacity of the territory, from the point of view of the development opportunities of solar power engineering, the data obtained by the scientists from the Perm State National Research University, who conducted the research of the solar radiation streams on the territory of Perm, research of other cities in the Perm Region for a number of years, were used, too. Figure 1 presents the location of these cities on geographical map of Russian Federation.

Table 1. List of Russian cities by their geographical position from the south to the north

Cities	Geographical position: north latitude
Vladivostok	43°06'20"
Sochi	43°35'57"
Astrakhan	46°20'58"
Rostov-on-Don	47°13'52"
Chita	52°01'54"
The Petropavlovsk-Kamchatsky	53°02'39"
Omsk	54°59'32"
Novosibirsk	55°02'29"
Moscow	55°45'07"
Yekaterinburg	56°51'06"
Perm	58°00'37"
St. Petersburg	59°56'19"
Petrozavodsk	61°47'05"
Arkhangelsk	64°32'24"

Within the performance of the government contractual work, the task of studying the question of technical use possibility of solar energy was set for the authors in the regions of their residence – cities of Perm and Yekaterinburg. Therefore, the materials and calculations presented in the article are limited by these two regions of the Russian Federation only.

Experimental results and discussion

The Sverdlovsk Region and especially the Perm Region are the areas with the hilly terrain and on the territory of the Perm Region. There is a significant part of the Ural Mountains situated.

Calculations of the total solar radiation falling on the inclined surfaces are made with the use of the hour sums of the straight line disseminated and the reflected radiation falling on the horizontal surface

Figure 1. Map of Russian Federation

under the average conditions of overcast, considering anisotropism of the distribution of scattered radiation.

To this purpose, the model developed by Hay, considering the main feature of the angular distribution of scattered radiation – a maximum of its intensity in a circumsolar zone, is used in this research [16]. Quantitatively, it is very difficult to define borders of the isotropic approach admissibility for the reflected radiation, therefore in calculating the total radiation, falling on the solar-receivers focused to the south share of the reflected radiation in this model is defined approximately in the assumption of the isotropy of its distribution. Total daily incidence of radiation on an inclined surface in this case is represented by the following expression:

$$Q_\alpha = S\int_{t1}^{t2} \cos\theta \, \mathrm{d}t + D_\alpha + Q\,A_k\,\frac{1-\cos\alpha}{2} \tag{1}$$

$$D_\alpha = D\left[\left(\frac{Q-D}{E}\right)\frac{\cos\theta}{\cos Z} + \left(1-\frac{Q-D}{E}\right)\cos^2\frac{\alpha}{2}\right] \tag{2}$$

The direct radiation incidence on an inclined surface of S_α is defined by the direct radiation on a perpendicular surface of $S_\perp$ in the relation:

$$S_\alpha = S_\perp \tag{3}$$

$$S_\perp = [\cos(\varphi-\alpha)\cos\delta\cos\tau + \sin(\varphi-\alpha)\sin\delta] \tag{4}$$

On the basis of the year supervision of the sunshine duration in the territory of the analyzed regions, an annual incidence on the direct solar radiation on a horizontal surface in the clear sky, at overcast, the annual sum of the scattered radiation in the clear sky and overcast, the data allowing to estimate the power capacity of Perm and Yekaterinburg, from the point of view of the solar power engineering development, were obtained (tab.2).

Table 2. Indicators of power potential in solar power engineering in Yekaterinburg and Perm

Order	Variables	Yekaterinburg	Perm
1	Northern latitude	56°51'	58°00'
	East longitude	60°36'	56°15'
2	Sunshine duration – all in a year, [h]	1900-2100	1700-1800
3	Maximum – July, [h]	295	290
4	Minimum – December, [h]	36	30
5	Anual incidence of direct solar radiation on a horizontal surface in the clear sky (possible incidence), [MJ/m^2]	4560.24	4234
6	Maximum of solar energy-incidence – June, [MJ/m^2]	645.12	742
7	Minimum of solar energy-incidence – December, [MJ/m^2]	100.06	30
8	Average Solar Radiation [kW/m^2] Maximum – July	5.72	1.12
9	Average Solar Radiation [kW/m^2] Minimum – December	0.44	0.21
10	Period of effective use of solar-energy resources	April-September	May-August

The dynamics of the annual direct solar radiation incidence on a horizontal surface in the clear sky in Perm and Yekaterinburg is given in fig. 1. As the given analysis showed, in Perm the annual duration of the sunshine averages in a year are about 1770 hours, and the period with positive radiation balance makes 8 months. Transition of radiation balance from the negative value to the positive one takes place in March, and the return change is noticed in October. The annual incidence of direct solar radiation on the horizontal surface in the clear sky (*i. e.* possible incidence) makes 4234 MJ/m^2.

During a year, the maximum monthly amount of the direct radiation on the horizontal surface in June is 742 MJ/m^2, and the minimum in December – 30 MJ/m^2. Clouds significantly reduce the flow of direct solar radiation and the average cloudiness of the annual amount of direct solar radiation is reduced to 1824 MJ/m^2 in June to 360 MJ/m^2, in December it is up to 6 MJ/m^2. The annual sums of the scattered radiation in the clear sky make 1276 MJ/m^2. Considerable overcast increases scattered radiation almost by time and half. As a result, under the real conditions of the overcast annual solar energy incidence of the scattered radiation increases to 1894 MJ/m^2.

The annual total solar radiation incidence on the horizontal surface in the clear sky makes 5510 MJ/m^2. Overcast reduces the size of the total radiation to 3718 MJ/m^2. The maximum of the possible monthly sums of the total radiation fall in June – 904 MJ/m^2, and a minimum in December – 53 MJ/m^2.

In Perm, in summertime, in connection with a big time lag of the light day, the number of the sunshine hours increases till 10 a.m. From May to August, only 1-3 days a month without the sun are observed. In December, under the conditions of the shortest day, the duration of the sunshine does not exceed 30 hours, and the longest daily duration of the sunshine makes only 2.4-2.9 hours. During this period 21-23 days a month can be without the sun.

In city of Yekaterinburg, the annual duration of the sunshine averages in a year about 2010 hours, and the period with positive radiation balance makes 9 months. The annual arrival of the direct solar radiation on the horizontal surface in the clear sky makes 4560 MJ/m^2. In the annual course the maximum of the possible monthly sums of direct radiation on the horizontal surface falls in June – 645 MJ/m^2, and the minimum in December – 101 MJ/m^2.

In Yekaterinburg, in summertime, in connection with the long duration of light day, the number of the sunshine hours increases till 10 a. m. The minimum number of days without the sun is observed from April to September. In December, under the conditions of the shortest day, the duration of the sunshine does not exceed 30 hours, and the longest daily duration of light day makes only 6 hours 45 minutes. During this period 20-22 days a month can be without the sun.

In calculating the power potential of solar power engineering the actual insolation, which is defined on the basis of the supervision, has a major importance. The actual insolation on a given site of a surface depends on the width of the district and the season, on its orientation concerning the South, the corner to the horizon, the building configuration around, trees, the ambient temperature. The main is the width of the district which is defined by the zones and seasonality of the distribution of solar radiation. On the equator the hade of the sunshine on a terrestrial surface is maximal, and to the poles its continuous reduction is observed. Since between the angle of the sunshine incidence and the quantity of solar radiation there is an accurate dependence, from the equator to the poles the size of solar radiation decreases, so do the solar power engineering potential and solar collectors efficiency. Both estimated territories are located close to the polar circle and therefore, have much lower insolation than the southern regions of Russia.

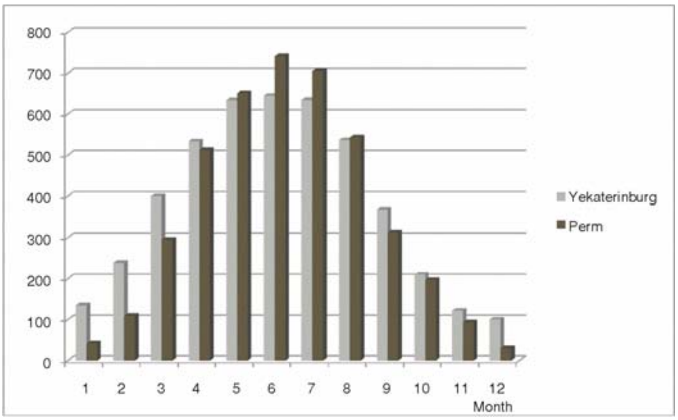

Figure 2. Dynamics of the direct solar radiation incidence on a horizontal surface in the clear sky in Perm and Yekaterinburg (MJ/m^2 per month)

As the research results show, in Yekaterinburg, the size of *the technical acceptability* of the solar radiation by Veynberg's criteria is sufficient for the development of solar power engineering (even in December its size makes 0.44 kW/m^2, at limit of the intensity of 0.42 kW/ m^2), and in the Perm Region it is much less – 0.21 kW/m^2. Further comes the comparative analysis the city of Perm (Perm Region) and Yekaterinburg (Sverdlovsk Region) with other cities of Russia, selected for the current analysis (fig. 2). The given comparison was carried out by three main following criteria:

– the rate of the average annual amount of solar radiation per unit of horizontal surface with respect to the climate conditions (frequency and strength of the clouds),
– the month low rate of solar radiation per unit of horizontal surface with respect to the climate conditions (frequency and strength of the clouds), and
– the indicator of a monthly maximum of sunlight on unit of a horizontal surface taking into account the climate conditions (frequency and force of overcast). Intermediate calculations of the values of these criteria are given in *Appendix* (tab. A1-A3) [15].

As can be seen in tab. A1-A3 [15] among the analyzed major Russian cities the situation with the amount of the solar radiation throughout the year, by month and in total for the year, is not the same. Thus, the city of Vladivostok, ranking 1 and 3 in terms of the average annual and month amount a low solar radiation per unit of the horizontal surface with respect to climate conditions (frequency and strength of cloudiness) significantly legs behind other cities analyzed for the indicators month high solar radiation, taking into account climate conditions. This is because the gap in the intensity of the solar radiation between months throughout the year in this region is the smallest of all analyzed: the difference in the maximum and minimum amount of the solar energy throughout the year is only 59%, while in Arkhangelsk – 99.3% (4 MJ/m^2 or 1.1 kWh/m^2 in December and 575 MJ/m^2 or 159.7 kWh/m^2 in June).

The results of the study (tab. 3) revealed that for these areas, the inflow of direct solar radiation is insufficient for its technological use for a longer time of year, especially in the winter months. For Perm the period of effective use of solar energy resources is only May-August, whereas for Yekaterinburg, it is April-September.

Table 3. Ranking of Russian cities by main indicators of solar activity

Cities	City Rank (totally by year)	City Rank (monthly minium)	City Rank (monthly maximum)	Geographical co-ordinates, northern latitude
Vladivostok	3	1	14	43°06'20"
Sochi	2	2	2	43°35'57"
Astrakhan	1	3	1	46°20'58"
Rostov-on-Don	4	6	3	47°13'52"
Chita	5	4	5	52°01'54"
Petropavlovsk-Kamchatsky	8	5	13	53°02'39"
Omsk	6	7	6	54°59'32"
Novosibirsk	7	8	7	55°02'29"
Moscow	10	10	10	55°45'07"
Yekaterinburg	9	9	8	56°51'06"
Perm	11	11	4	58°00'37"
St. Petersburg	14	13	11	59°56'19"
Petrozavodsk	12	12	9	61°47'05"
Arkhangelsk	13	14	12	64°32'24"

Conclusions

This study focused on an assessment of potential of solar radiation of the Russian regions for development of the solar power. The question of possibility of industrial use of the solar energy for electricity generation and heat in the large cities of Russia was raised. In the course of research the following conclusions were revealed.

- Some cities of Russia located in the central and northern territories such as Chita, Perm, Omsk and others, have high rating estimates on intensity of sunlight in summer months. It creates illusion of possibility of development of solar power in these regions.

- An assessment of the general potential of receipt of solar radiation in a year, total solar radiation in these regions and their fluctuations on months within a year allowed to draw a conclusion that industrial use of solar energy for electricity generation and heat in these cities of Russia inefficiently.

This work is part of a larger research program devoted to studying of possibility of using solar activity in Russia.

Acknowledgments

The work is carried out based on the task #2014/152 on the fulfillment of the government contractual work in the field of scientific activities as a part of base portion of the state task of the Ministry of Education and Science of the Russian Federation PNIPU (topic #1487).

Nomenclature

A_k – albedo of a terrestrial surface, [const]
D, Q – the scattered and total radiation incidence
– on a horizontal surface [MJm^{-2}]
E – extra-atmospheric radiation, [MJ]
$t1$ – sunrise time, [date/time]
$t2$ – sunset time, [date/time]
Z – antiaircraft corner of the sun, [°]

Greek symbols

α – surface tilt angle to the horizon, [°]
δ – inducement of the Sun
φ – width of a place
θ – hade of direct sunlight, [°]
τ – hour corner of the Sun

References

[1] Angelis-Dimakis, A., *et al.*, Methods and Tools to Evaluate the Availability of Renewable Energy Sources, *Renewable and Sustainable Energy Reviews, 15* (2011), 2, pp. 1182-1200
[2] Dincer, I., Environmental Impacts of Energy, *Energy Policy, 27* (1999), 14, pp. 845-854
[3] Varun, P. R., Bhat, I. K., Energy, Economics and Environmental Impacts of Renewable Energy Systems, *Renewable and Sustainable Energy Reviews, 13* (2009), 9, pp. 2716-2721
[4] Dincer, I., Rosen, M. A., Thermodynamic Aspects of Renewables and Sustainable Development, *Renewable and Sustainable Energy Reviews, 9* (2005), 2, pp. 169-189
[5] Domniguez, J., Amador, J., Geographical Information Systems Applied in the Field of Renewable Energy Sources, *Computers and Industrial Engineering, 52* (2007), 3, pp. 322-326
[6] Posso, F., *et al.*, Estimation of the Solar Energy Potential in Venezuela by Using Geographic Information Systems, *Revista Geografica Venezolana, 55* (2014), 1, pp. 27-43
[7] Isakov, S., Shklyaev, V., Assessment of Receipt of Solar Radiation on Natural Surfaces with Application of Geographic Information Systems, *Geographical Bulletin, 53* (2012), 1, pp. 72-80
[8] Isakov, S., Shklyaev, V., Use of Cards of Differential Albedo for an Assessment of Thermal Effect of "the City Island of Heat" with use of Geographic Information Systems, in: *Geo-Information Ensuring Spatial Development of Perm Region*, Publishing house of the Perm University, Perm, Russia, 2011, pp. 59-64
[9] Danilov, V., *et al.*, Experiment of Efficiency of the Combined System of Solar Heat-Generation, *Alternative Power Engineering and Ecology, 3* (2012), pp. 77-81
[10] Nikolaeva, L., Kabaloyev, D., Using of Solar Energy as the Alternative Source, *Proceedings*, International Scientific and Technical Power Supply and Energy Saving Agriculture Conference, Moscow, 2006, Vol. 1, pp. 350-351
[11] Abramovich, B., Sychev, Y., Intellectual System of Complex Monitoring of Using Energy Resources and Control of the Level of Quality of Electric Energy in Conditions of the Distributed Generation on the Basis of Alternative and Renewables Energy Sources, *Industrial Power, 12* (2014), pp. 40-44
[12] Valov, M., *et al.*, About the Accuracy of Determining the Intensity of Solar Radiation in the Calculations of Solar Energy, *Solar Engineering, 6* (1982), pp. 47-50
[13] Veynberg, B., Experience of Climatological Characteristics of the Area for Satisfaction of Inquiries of Solar Technology, *Meteorological News, 1-2* (1933), pp. 35-38
[14] Veynberg, B., *Gelio-Energetic Resources of the USSR. Atlas of Energy Resources of the USSR*, United Scientific and Technical Publishing House, Moscow, 1935

[15] ***, Annual Report on an Assessment of Regional Features of Climate Change of Willows Regions in Russia and Belarus, Report No. 1, Climatic Center of ROSHYDROMET, Moscow, 2007
[16] Hay, J., E., Calculation of Monthly Mean Solar Radiation or Horizontal and Inclined Surfaces, *Solar Energy, 23* (1979), 4, pp. 301-307

Appendix

Table A1. Rank of Russian cities by the rate of the average annual amount of solar radiation per unit of horizontal surface with respect to climate conditions (frequency and strength of the clouds)

City rank	Cities	Totally per year [MJm^{-2}]	Monthly minimum (December) [MJm^{-2}]	Monthly maximum (June/July) [MJm^{-2}]
1	Astrakhan	4940.00	95.80	755.60
2	Sochi	4910.00	124.90	744.50
3	Vladivostok	4640.00	208.10	518.00
4	Rostov-on Don	4600.00	80.00	678.00
5	Chita	4360.00	88.00	643.00
6	Omsk	4010.00	56.00	640.00
7	Novosibirsk	4000.00	56.00	638.00
8	Petropavlovsk-Kamchatsky	3950.00	83.90	560.90
9	Yekaterniburg	3760.00	46.00	615.00
10	Moscow	3670.00	42.10	600.10
11	Perm	3490.00	13.80	645.42
12	Petrozavodsk	3100.00	8.60	601.60
13	Arkhangelsk	3060.00	4.00	575.00
14	St. Petersburg	3020.00	8.00	578.00

Table A2. Rank of Russian cities by monthly low rate of the solar radiation per unit of horizontal surface with respect to climate conditions (frequency and strength of the clouds)

City rank	Cities	Totally per year [MJm^{-2}]	Monthly minimum (December) [MJm^{-2}]	Monthly maximum (June/July) [MJm^{-2}]
1	Vladivostok	4640.00	208.10	518.00
2	Sochi	4910.00	124.90	744.50
3	Astrakhan	4940.00	95.80	755.60
4	Chita	4360.00	88.00	643.00
5	Petropavlovsk-Kamchatsky	3950.00	83.90	560.90
6	Rostov-on-Don	4600.00	80.00	678.00
7	Omsk	4010.00	56.00	640.00
8	Novosibirsk	4000.00	56.00	638.00
9	Yekaterinburg	3760.00	46.00	615.00
10	Moscow	3670.00	42.10	600.10
11	Perm	3490.00	13.80	645.42
12	Petrozavodsk	3100.00	8.60	601.60
13	St. Petresburg	3020.00	8.00	578.00
14	Arkhangelsk	3060.0	4.00	575.00

Table A3. Ranking Russian cities by indicator of a monthly maximum of sunlight on unit of a horizontal surface taking into account climate conditions (frequency and force of overcast)

City rank	Cities	Totally per year, [MJm^{-2}]	Monthly minimum (December) [MJm^{-2}]	Monthly maximum (June/July) [MJm^{-2}]
1	Astrakhan	4940.00	95.80	755.60
2	Sochi	4910.00	124.90	744.50
3	Rostov-on-Don	4600.00	80.00	678.00
4	Perm	3490.00	13.80	645.42
5	Chita	4360.00	88.00	643.00
6	Omsk	4010.00	56.00	640.00
7	Novosibirsk	4000.00	56.00	638.00
8	Yekaterinburg	3760.00	46.00	615.00
9	Petrozavodsk	3100.00	8.60	601.60
10	Moscow	3670.00	42.10	600.10
11	St. Petersburg	3020.00	8.00	578.00
12	Arkhangelsk	3060.00	4.00	575.00
13	Petropavlovsk-Kamchatsky	3950.00	83.90	560.90
14	Vladivostok	4640.00	208.10	518.00

Paper submitted: March 30, 2015
Paper revised: May 14, 2015
Paper accepted: May 26, 2015