Research of solar energy potential in the Eastern Siberia

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Abstract. The article presents the results of solar energy potential studying in the Eastern Siberia region (in particular the Irkutsk Oblast) of the Russian Federation by integrating data from three databases: observatories of the CIS countries, NASA and the Hong Kong Observatory. The analysis of the databases was carried out taking into account their error degree. The results obtained make it possible to identify the year periods in when solar power plants can be used as efficiently as possible, both for generating thermal energy and electricity. In turn it will allow optimizing both the solar stations and the design of the solar panels and collectors themselves. The research methodology presented in this article can also be applied to assess the solar energy potential in other regions of the Russian Federation, which can be used for systematizing the data obtained for further calculations of solar plants required capacity and their design.

1. Introduction

Renewable energy is constantly evolving, and technologies for converting alternative energy sources are improving. One of the most perspective directions in this area is solar energy. There are many studies [1-10] and discoveries, as well as many types of solar power plants [11-17].

According to the book of A.M. Magomedov "Unconventional renewable energy sources" [18] the solar constant is the amount of Sun radiant energy in the entire wavelength range, received per time unit by an area unit placed perpendicular to the sun rays and outside the Earth's atmosphere at a distance of one astronomical unit from the Sun. The solar constant value obtained as a result of direct measurements from spacecraft and recommended by NASA as a standard:

\[ I_0 = 1353 \text{ W/m}^2 \pm 1.5 \% \]

As a result of passing through the Earth's atmosphere, a part of the sun's radiation is reflected and only about 80% of the solar constant value reaches the Earth's surface. The amount of solar energy reaching the Earth's surface differs from the average annual value: in winter - by less than 0.8 kW·h/m² per day and by more than 4 kW·h/m² per day in summer in Northern Europe. The difference decreases with getting closer to the equator. The amount of solar energy also depends on the geographical location of the site: with getting closer to the equator the energy amount increases. For example, the average annual total solar radiation falling on a horizontal surface is approximately: in Central Europe, Central Asia and Canada 1000 kW·h/m²; in the Mediterranean 1700 kW·h/m²; in most desert regions of Africa, the Middle East and Australia 2200 kW·h/m². Thus, the amount of solar radiation varies significantly depending on the season and geographic location.
2. Analysis of observatory databases using the integration method

According to the Institute of Energy Strategy, the theoretical solar energy potential in Russia is more than 2300 billion tons of fuel equivalent and the economic potential is 12.5 million tons of fuel equivalent. The solar energy potential entering the territory of Russia within three days exceeds the energy getting from the entire annual electricity production in our country.

Due to the location of the Russian Federation (from the 41-st to 82-n degrees latitude north), the level of solar radiation varies significantly: from 810 kWh/m² per year in the remote northern regions to 1400 kWh/m² per year in the southern regions. The level of solar radiation is also influenced by large seasonal fluctuations: at a latitude of 55 degrees, solar radiation in January is 1.69 kWh/m², and in July - 11.41 kWh/m² per day.

The solar energy potential is greatest in the southwest (North Caucasus, the Black and Caspian Seas) and in South Siberia and the Far East.

The most perspective regions for solar energy using are: Republic of Kalmykia, Rostov Oblast, Krasnodar Krai, Volgograd Oblast, Astrakhan Oblast and other regions in the south-west, also Altai Krai, Primorsky Krai, Irkutsk Oblast, Chita Oblast, Republic of Buryatia and other regions in the south-east. Moreover, in some regions of Western and Eastern Siberia and the Far East the level of solar radiation exceeds the level of the southern regions. According to the atlas of solar energy resources in Russia, authored by O.S. Popel and S.E. Frid [19], in Irkutsk (52 degrees latitude north) the average annual solar radiation level reaches values from 4 to 4.5 kW-hour/m²-day.

The Hong Kong Observatory has climatic data collected from cities around the world for a 30-year period (1961-1990). The data for Irkutsk are presented in Table 1:

| Table 1. Climatic data for Irkutsk according to the Hong Kong Observatory databases. |
|-----------------------------------------------|
| Jan. | Feb. | March | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. |
|-----------------------------------------------|
| Average air temperature, °C | -18.8 | -16.7 | -7.4 | 1.4 | 9.3 | 15.0 | 17.5 | 15.1 | 8.7 | 0.9 | -8.4 | -16.0 |
| The rainfall, mm | 12.0 | 8.5 | 12.8 | 18.9 | 32.9 | 61.9 | 120.1 | 82.6 | 50.2 | 29.9 | 18.3 | 19.1 |
| The number of cloudy days | 4.3 | 2.6 | 3.1 | 4.5 | 6.6 | 8.1 | 11.1 | 9.5 | 7.7 | 5.6 | 5.6 | 5.3 |
| Average daily sunshine duration, hours | 3.0 | 5.0 | 6.7 | 7.4 | 8.6 | 8.8 | 7.8 | 7.0 | 6.1 | 4.9 | 3.1 | 2.0 |

The NASA (National Aeronautics and Space Administration) database stores information about solar activity from all over the world for 22 years (July 1983 - June 2005). To obtain data for Irkutsk, it’s needed to enter its geographic coordinates in a special section on the NASA website and the database will provide all the necessary information. Table 2 will show the data obtained on the monthly average solar energy values falling on an optimally oriented surface located in Irkutsk.

| Table 2. The NASA databases for Irkutsk for 22 years. |
|-----------------------------------------------|
| Jan. | Feb. | March | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. | Mean |
|-----------------------------------------------|
| Average monthly solar radiation falling on a horizontal surface, kWh/m²/day | 1.15 | 2.20 | 3.73 | 4.83 | 5.55 | 5.49 | 5.00 | 4.2 | 6 | 3.28 | 2.15 | 1.30 | 0.88 | 3.32 |
| The deviation of the minimum and maximum values of solar activity falling a horizontal surface from the monthly average, % |
|-----------------------------------------------|
| Minimum value | -10 | -9 | -10 | -7 | -11 | -12 | -13 | -17 | -13 | -13 | -14 | -16 | -12 |
| Maximum value | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 |

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Table 4. Solar activity calculated data in Irkutsk.

| Year | Jan | Feb | March | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Mean |
|------|-----|-----|-------|-----|-----|------|------|-----|-----|-----|-----|-----|------|
| 2021 | 2.48 | 3.94 | 5.49  | 6.26 | 6.17 | 5.40 | 4.70 | 4.3 | 4.14 | 3.40 | 2.58 | 2.02 | 4.24 |

3. Estimation solar energy average monthly values

Knowing the number of cloudy days and the average length of daylight hours, it can be determined the total monthly and hourly solar activity for each month. It’s needed to subtract the number of cloudy days from the total number of days in a month, assuming that these days solar activity is either very small or absent altogether. The scattered radiation does not play a role in this case, because it can be used mainly in photoelectric conversion. Scattered solar radiation is not enough to carry out thermodynamic transformation. The calculations will be made for an optimally oriented surface and are summarized in Table 4.
Table 1. Duration of month, days

| Month | Days |
|-------|------|
| Jan   | 31   |
| Feb   | 28   |
| Mar   | 31   |
| Apr   | 31   |
| May   | 30   |
| Jun   | 31   |
| Jul   | 31   |
| Aug   | 30   |
| Sep   | 31   |
| Oct   | 30   |
| Nov   | 31   |
| Dec   | 365  |

Monthly average solar energy values falling on an optimally oriented surface, kW-h/m²-day

| Month | Value |
|-------|-------|
| Jan   | 2.48  |
| Feb   | 3.94  |
| Mar   | 5.49  |
| Apr   | 6.26  |
| May   | 6.17  |
| Jun   | 5.40  |
| Jul   | 4.70  |
| Aug   | 4.31  |
| Sep   | 4.14  |
| Oct   | 3.40  |
| Nov   | 2.58  |
| Dec   | 2.02  |
| Year  | 4.24  |

Average number of cloudy days in 30 years

| Year | Value |
|------|-------|
| 2000 | 4.3   |
| 2001 | 2.6   |
| 2002 | 3.1   |
| 2003 | 4.5   |
| 2004 | 6.6   |
| 2005 | 8.1   |
| 2006 | 11.1  |
| 2007 | 9.5   |
| 2008 | 7.7   |
| 2009 | 5.6   |
| 2010 | 5.6   |
| 2011 | 5.3   |
| 2012 | 74.0  |

Average daily sunshine duration, hours

| Year | Value |
|------|-------|
| 2000 | 3     |
| 2001 | 5     |
| 2002 | 6.7   |
| 2003 | 7.4   |
| 2004 | 8.6   |
| 2005 | 8.8   |
| 2006 | 7.8   |
| 2007 | 6.1   |
| 2008 | 4.9   |
| 2009 | 3.1   |
| 2010 | 2     |
| 2011 | 5.9   |

Total solar energy per month, kW-h/m²

| Year | Value |
|------|-------|
| 2000 | 66.22 |
| 2001 | 100.08|
| 2002 | 153.17|
| 2003 | 159.63|
| 2004 | 150.55|
| 2005 | 118.26|
| 2006 | 93.53 |
| 2007 | 92.67 |
| 2008 | 92.32 |
| 2009 | 86.36 |
| 2010 | 62.95 |
| 2011 | 51.91 |
| 2012 | 1233.8|

Average daily solar energy, kW-h/m²

| Year | Value |
|------|-------|
| 2000 | 0.83  |
| 2001 | 0.79  |
| 2002 | 0.82  |
| 2003 | 0.85  |
| 2004 | 0.72  |
| 2005 | 0.61  |
| 2006 | 0.60  |
| 2007 | 0.62  |
| 2008 | 0.68  |
| 2009 | 0.69  |
| 2010 | 0.83  |
| 2011 | 1.01  |
| 2012 | 0.72  |

Knowing the deviation of the minimum and maximum values of solar activity, it is possible to determine the maximum and minimum value of the monthly average value of solar energy falling on an optimally oriented surface. The calculations are presented in Table 5.

Table 5. Average monthly solar activity analysis.

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Value | 2.48 | 3.94 | 5.49 | 6.26 | 6.17 | 5.40 | 4.70 | 4.31 | 4.14 | 3.40 | 2.58 | 2.02 | 4.24 |
| Minimum value | -35 | -22 | -22 | -12 | -20 | -21 | -25 | -35 | -34 | -38 | -40 | -53 | -30 |
| Maximum value | 33 | 22 | 18 | 10 | 22 | 37 | 45 | 20 | 42 | 41 | 30 | 44 | 30 |
| The maximum value of the average monthly solar energy falling on an optimally oriented surface, kW-h/m²/day | 3.30 | 4.81 | 6.48 | 6.89 | 7.53 | 7.40 | 6.82 | 5.17 | 5.88 | 4.79 | 3.35 | 2.91 | 5.51 |
| The minimum value of the average monthly solar energy falling on an optimally oriented surface, kW-h/m²/day | 1.61 | 3.07 | 4.28 | 5.51 | 4.94 | 4.27 | 3.53 | 2.80 | 2.73 | 2.11 | 1.55 | 0.95 | 2.97 |
Difference between maximum and minimum value

|        | 1.69 | 1.73 | 2.20 | 1.38 | 2.59 | 3.13 | 3.29 | 2.37 | 3.15 | 2.69 | 1.81 | 1.96 | 2.54 |

Data from table 5 will be presented in the form of a diagram (Figure 1):

![Graph showing monthly average solar energy values falling on an optimally oriented surface, kW∙h/m²∙day.]

Figure 1. Monthly average solar energy values falling on an optimally oriented surface, kW∙h/m²∙day.

After analyzing the data obtained, it can be made the conclusion that the solar energy, falling on an optimally oriented surface, reaches its highest value in May (7.53 kW∙h/m²∙day) and June (7.40 kW∙h/m²∙day). The lowest value was recorded in December (0.95 kW∙hour/m²∙day). However, if to analyze the indicators of average monthly solar activity, it can be seen that it reaches its highest value in April (6.26 kWh/m²∙day) and May (6.17 kWh/m²∙day).

If to pay attention to the data presented in the diagram of the average daily values of solar energy (Figure 2), which is built on the basis of the data from table 4, it can be seen that the highest value is observed in December (1.01 kWh/m²). However, the monthly average value of solar radiation in December is lower than in all other months (2.02 kWh∙hour/m²∙day). It can be explained by the fact that December has the shortest daily sunshine duration (2 hours).
Figure 2. Average daily values of solar energy falling on an optimally oriented surface, kW·h/m²·day.

Figure 3 shows a diagram of total average value of solar energy falling on an optimally oriented surface for each month. This diagram shows that most of the usable solar energy can be obtained from March to May. At the same time, the maximum daily average value is observed in winter, and the maximum solar activity value was recorded in May, June and July. Such instability of indicators arises for a number of reasons below.

It can be seen from Table 2, that the lowest cloudiness for over 22 years was observed in winter (62.7 - 69.2%), therefore, at this time, the average daily value of solar activity reached the highest rates in a year. However, due to the fact that winter has the lowest sunny day duration, the average monthly and total average value per month during this period are minimal.

It was recorded the highest total average value for the month in the period from March to May, namely in April (159.63 kWh/m²). In April it was also recorded the highest monthly average solar radiation (6.26 kWh/m²·day), but the highest annual solar activity was observed in May (7.53 kWh/m²·day). Such instability of monthly indicators can be explained by the fact that the number of cloudy days and the percentage of cloudiness in May are higher than in April.
Figure 3. Total average value of solar energy falling on an optimally oriented surface per month, kW·h/m²·day.

4. General conclusions

It’s most profitable in the Irkutsk region to use solar plants during the period from March to October, and the greatest effect from the sun energy using can be achieved during the period from March to May. It is during this period that the sun position and the angle of sun rays falling on a normally oriented surface are most optimal for the Irkutsk region. In the period from November to February using of solar energy is ineffective due to the fact that during this period the length of daylight hours is very small.

The research presented in this article confirms the fact that the solar radiation level falling on a particular surface does not directly depend on the outside air temperature, wind speed and humidity level. It depends on the cloud level and the geographic location of the surveyed area. Therefore, in developing solar collectors and panels, the main tasks are to save solar energy falling on a special surface, select a suitable location for this surface, as well as convert solar radiation into useful energy with the highest efficiency and the least energy loss.

The research technique presented in this article can be used for research on optimization of the newly developed solar power design plants and solar systems in general [20-24]. Thus, this technique has been applied in developing of two types of solar collectors with a design optimized for efficient using in the Eastern Siberia region. There were obtained patents for a useful model [25-26] for these models of solar collectors.

In SP.131.13330.2018 «Building climatology» are shown the table 8.1 «The value of the total solar radiation (direct and scattered) falling on a horizontal surface with a cloudless sky» and table 9.1 «The value of the total solar radiation (direct and scattered) falling on a vertical surface with a cloudless sky». These tables are used for the solar systems designing.

The data obtained in this article make it possible to calculate the solar energy falling on a surface oriented along the normal to the sun rays direction. It means that the inclination angle of the solar plant coincides with the geographical latitude of the area. This inclination angle allows the receiving surface to get the biggest amount of solar energy. Thus, the data obtained in the result of the presented research supplement the normative data and expand the possibilities of solar systems designing.
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