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CLIMATE RESOURCE POTENTIAL TO DEVELOP SOLAR POWER IN BELARUS

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Abstract. The work analyses climate resources that can potentially be used to develop solar power in Belarus efficiently. The authors determine space-time variability of radiation regime including such parameters as solar irradiance, atmosphere transparency, sunshine duration, cloud cover patterns, etc. The efficiency of solar power generators is assessed by taking into account the number of clear days with low cloud cover per year, sunshine duration per month, and solar irradiance of a horizontal surface in the daytime.
Keywords: solar irradiance, sunshine duration, cloud cover, solar power potential.

1 Introduction

Solar power is being developed in the United States, Western Europe, China, Japan, and South Korea most intensively. Bloomberg New Energy Finance (BNEF) predicts that the share of renewable energy sources will account for almost 3/4 of the world's investment in power generation by 2040. BNEF estimates that in the next 22 years $ 10.2 trillion will be spent on electricity production in the world. $ 7.4 trillion of it will be spent on clean energy [1]. $ 2.8 trillion is expected to be invested in solar energy by 2040, resulting in a 14-fold increase in capacity. As a result, by 2040 wind and solar electricity will account for 48% of the world's installed capacity and 34% of electricity production, compared with 12 and 5% at present. Renewable energy is also expected to reach 74% in Germany by 2040, 38% in the US, 55% in China and 49% in India [1]. The EU has begun to generate and consume 50 times more solar energy over the past ten years.

The European Union supports Belarus' transition to solar energy by implementing the EU4Energy initiative. Developing solar power allows us to reduce partially our dependence on hydrocarbons and suppliers-monopolists while providing maximum environmental friendliness of energy production. Modern equipment, including the equipment of home manufacture, even now allows achieving a return on capital investments within a specified time frame. At present, the share of renewable energy sources in Belarus is 5.1% [2]. It is planned to bring this figure to 9% by 2035. Today, 108 power plants with the total capacity of about 250 MW are already in operation in Belarus converting solar energy into

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electricity. It is a rather modest figure but it has significant reserves for growth. In order to provide high efficiency of solar technology in Belarus it is necessary to scientifically study such features of our climate as spatial variability of factors that affect solar irradiance of the ground surface.

2 Method

To estimate how feasible it is to develop solar energy in a particular area, we should take into consideration thermal energy resources of its climate, i.e. characteristics of radiation regime which result from solar radiation [3]. Many factors influence distribution of solar energy and its transformations in the atmosphere. The main ones [4] are: types of cloud cover; profiles of temperature, water vapour and ozone; presence of dust and haze in the atmosphere; spectral properties of the underlying surface; concentration of CO_2 in the atmosphere; air pressure at the level of the Earth's surface, etc.

There is a lot of research that estimates solar energy resources of climate in Belarus [5, 6, etc.], regions of Russia [7, 8, 9, 10, etc.] and other countries. All these works present similar statistical generalizations of radiation regime parameters. They conclude that the conditions are quite suitable to develop solar power despite the significant territorial remoteness and quantitative differences in the parameters under consideration. Space-time variability of the estimated parameters needs to be detailed. As actinometric observation data are often limited, it is necessary to apply methods of analytical calculations and forecasting more widely. At present it is also essential to estimate environmental impact of developing solar power in a region by taking into account current and predicted climatic fluctuations. Many researchers [11, 12, 13, 14, 15, 16, etc.] focus on this issue.

This research is based on the data which characterize radiation regime, cloudiness and other atmospheric phenomena on the territory of Belarus [17]. The time series are taken for the 41-year representative period (1979–2019) at 11 meteorological stations where actinometric parameters are recorded. Certain problems related to representativeness of data may occur when we need to generalize spatial information concerning large areas. In this regard, it makes sense to employ external resources and data from neighbouring countries or from such information sources and databases as NASA SEE; ESRA 1996, 2000; WRDC; Meteonorm 4.0; S@tel-Light, etc. All these databases differ in forms of presenting information, sets of characteristics, data cost, periods of averaging and the number of weather stations presented. The authors of this research used such methods of statistical processing of experimental data as regression analysis, time series analysis, spatial generalization of meteorological information, etc. Methods of analytical calculations and mapping are also applied here.

It is noted that the construction, operation and eventual decommissioning of solar energy facilities affect the environment and ecosystem biodiversity. In work [11] the researchers say that the installation of solar power plants on the ground leads to removal of vegetation and landscape fragmentation. Transmission corridors create barriers to the movement of species and their genes [18]. An analysis of water use for maintaining solar power plants in the southwest of the EU indicates that water for dust control is the main component (60-99%) of total water consumption [15]. It should also be borne in mind that water is often used in water cooling systems necessary for solar power facilities. In this regard, there may be a certain hydrochemical and hydrological impact on the environment. The installation of solar power plants may require extensive landscape modification which involves removal of vegetation, land transformation, soil compaction and infrastructural construction. All these activities increase risks for water and wind erosion [13]. Photovoltaic cells must be properly disposed of at the decommissioning stage to prevent environmental contamination with toxic materials contained in the cells. If improperly handled, industrial waste can pose hazards to air quality, health of the public and the environment, surface and ground water, in particular [15].

Strong heating of air caused by solar radiation concentrated by mirror reflectors and passing through the air leads to changes in humidity, heat balance and wind direction. This results in adverse environmental impacts on ecosystems in the areas where large power plants are located. The radiation balance at the level of the ground surface can change when the albedo of photovoltaic cells differs from the original background albedo. With their absorbing capacity, photovoltaic panels have an effective albedo (on average 0.18-0.23). Some studies [14] have shown that the installation of solar panels leads to a decrease in the surface albedo and an increase in the surface temperature by 0.4 ° C. Albedo in cities is usually 0.15-0.22. Therefore, the photovoltaic panels installed on rooftops have a potential to increase albedo resulting in the cooling effect. We already mentioned the importance of this problem in relation to thermal pollution of urbanized areas [19]. It was found out that the air temperature dropped by 0.2 ° C under the panels with higher efficiency [14].

Everything mentioned above allows us to conclude that climatic resources play a crucial role in developing solar power both for making decision to install and maintain solar energy facilities in a certain area and for assessing their impact on the environment. The development of "green" energy is the future of mankind, though [20].

3 Results and discussion

Feasibility to operate solar energy facilities in a certain area and their efficiency depend on a number of meteorological factors including the intensity of solar radiation (kW / m^2) and air temperature (° C). Solar radiation reaching the ground surface can be characterized by the following indicators: direct, diffuse and total radiation, reflectivity of the underlying surface, radiation balance, sunshine duration (SD), cloud cover patterns, the number of cloudy and clear days with different cloud gradations, etc.

Solar radiation data characterize different time periods: a year, a season, a month, a decade and a day. In paper [6] it is noted that different-scale variability of solar radiation reaching the ground surface is not taken into account in the same way in solar energy calculations. However, we believe that diurnal differentiation is the most acceptable. Daily values allow easy switching to ten-day, monthly and annual calculations.

As we are short of actinometric data, we developed a method to calculate daily values of total solar radiation [21, 22]. The calculated monthly and annual amounts are shown in Table 1.

Table 1. Total solar radiation, MJ / m^2.

Month / Meteorological station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Minsk	58	127	276	420	571	615	608	494	329	190	79	37	3804
Brest	73	143	291	431	576	618	610	500	341	206	94	51	3933
Homel	71	140	288	429	575	618	610	499	389	203	92	49	3912
Grodno	59	129	278	422	573	619	610	494	330	191	80	37	3822
Vitebsk	46	116	265	414	571	621	610	488	328	177	67	25	3729
Mogilev	57	127	277	422	574	619	609	492	327	188	78	35	3805

Our comparing the calculated and measured values of the total solar radiation at Minsk and Vasilevichi meteorological stations revealed that the annual radiation amounts differ by no more than 1–2%. There is a high convergence of the results in most months of the year. However, in January, October, and November deviations can reach 16–25 %. This can be explained by the fact that the last official data of generalizations were registered in 1980 and do not take into account the temporal variability of total solar radiation over the past forty years.

In order to analyse a natural solar energy potential of an area, it is customary to represent it in its intensity units, kW * h / m^2. In this regard, we applied the ratio of 1 kW * h / m^2 as equal to 3.6 MJ / m^2. According to B.P. Weinberg [23], the total solar radiation is considered "technically acceptable" when its intensity is 0.60 kW / m^2 or higher. The performed calculations showed that in December and January this level of radiation intensity is not reached on the territory of Belarus. For example, in Minsk it reaches 0.34 and 0.54 kW * h / m^2 per day, respectively. The highest rate of 5.69 kW * h / m^2 per day is in June (Table 2).

Table 2. Intensity of total solar radiation per day, kW * h / m^2.

Month / Meteorological station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Minsk	0.5	1.3	2.5	3.9	5.1	5.7	5.5	4.4	3.0	1.7	0.7	0.3	2.9
Brest	0.6	1.4	2.6	4.0	5.2	5.7	5.5	4.5	3.2	1.8	0.9	0.5	3.0
Homel	0.6	1.4	2.6	4.0	5.2	5.7	5.5	4.5	3.1	1.8	0.8	0.5	3.0
Grodno	0.5	1.3	2.5	3.9	5.1	5.7	5.5	4.4	3.1	1.7	0.7	0.3	2.9
Vitebsk	0.4	1.1	2.4	3.8	5.1	5.8	5.5	4.4	3.0	1.6	0.6	0.2	2.8
Mogilev	0.5	1.3	2.5	3.9	5.1	5.7	5.5	4.4	3.0	1.7	0.7	0.3	2.9

Our calculations show that "technically acceptable" radiation on the territory of Belarus occurs from 289 (Braslav) to 321 (Bragin) days a year (79–88%). Its distribution depends on the latitude. The intensity of solar radiation of 0.60 kW / m^2 is not provided in Belarus from November 14-30 to January 12-28. In general, however, it is necessary to state that the solar power potential of Belarus is quite high, despite certain seasonal fluctuations.

Most researchers estimate the total solar radiation by using empirical relationships with sunshine duration and cloudiness grade. The intra-annual variation of total and low cloud cover, averaged over the territory of Belarus, is shown in Fig. 1.

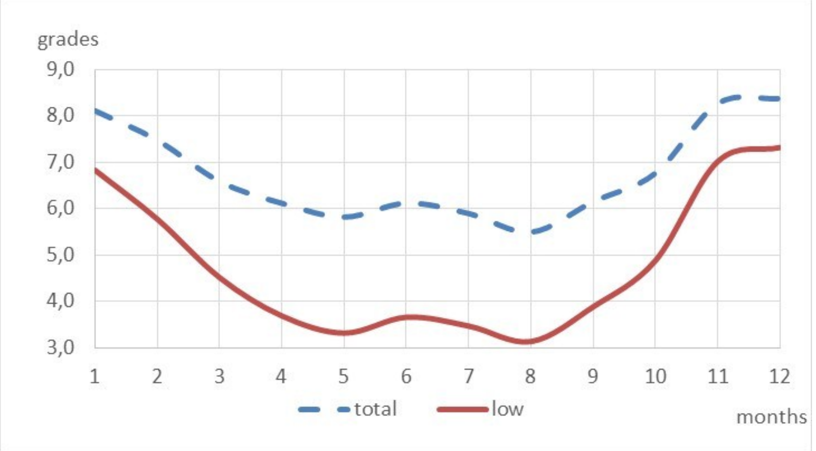
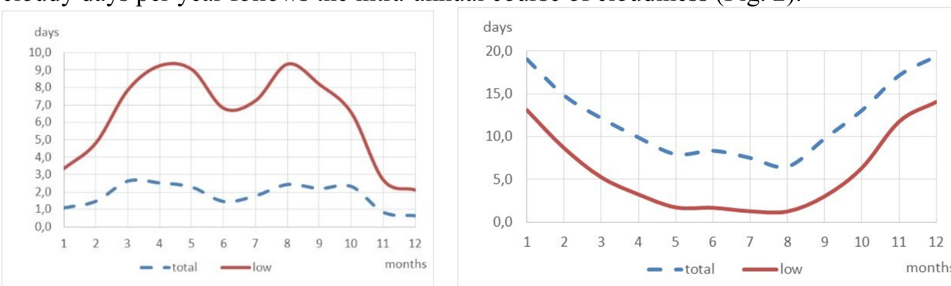


Fig. 1. The course of total (blue) and low (brown) cloud cover in Belarus within a year.

Fig. 1 shows the most typical picture for northern Europe, i.e. the lowest values of cloud cover are characteristic of the warm period with a slight increase in June and a sharp growth in winter when the Atlantic influence is great. The average number of clear and cloudy days per year follows the intra-annual course of cloudiness (Fig. 2).



(a) (b)

Fig. 2. The number of clear (a) and cloudy (b) days (with different types of cloudiness) per year in Belarus.

The largest number of clear days falls on the warm period from April to September with a slight decrease in June due to the prevailing precipitation regime. The number of clear days per year may indicate indirectly the prospects to develop solar power. Some scientists note that the highest efficiency of solar panels is provided when the number of clear days with low clouds per year exceeds 200 [7]. However, in Belarus this indicator is a little more than 60 on average, reaching 100-105 days at certain meteorological stations only in some years. Thus, the number of clear days with low cloud cover cannot be taken as a criterion to estimate solar power potential in Belarus.

The number of clear days with total cloud cover increases from the north, north-west to the south, southeast across Belarus: from 20 (Grodno, Polotsk, Mogilev) to 30-35 days (Mozyr, Bragin) and with low cloudiness from 50 (Vysokoje) to 100 days (Mozyr, Pinsk, Zhlobin) (Fig. 3). There is also a decrease in the number of cloudy days with total cloud cover from 160 (Polotsk, Sharkovshchina) to 120 days (Bragin, Mozyr) and with low cloud cover from 120 (Borisov, Lepel, Senno) to 60 days (Vasilevichi, Pruzhany) (Fig. 4). It should be noted that, unlike the duration of sunshine, the cloudiness parameters are characterized by significant spotting on the maps, which implies a search for a relationship with the landscape patterns.

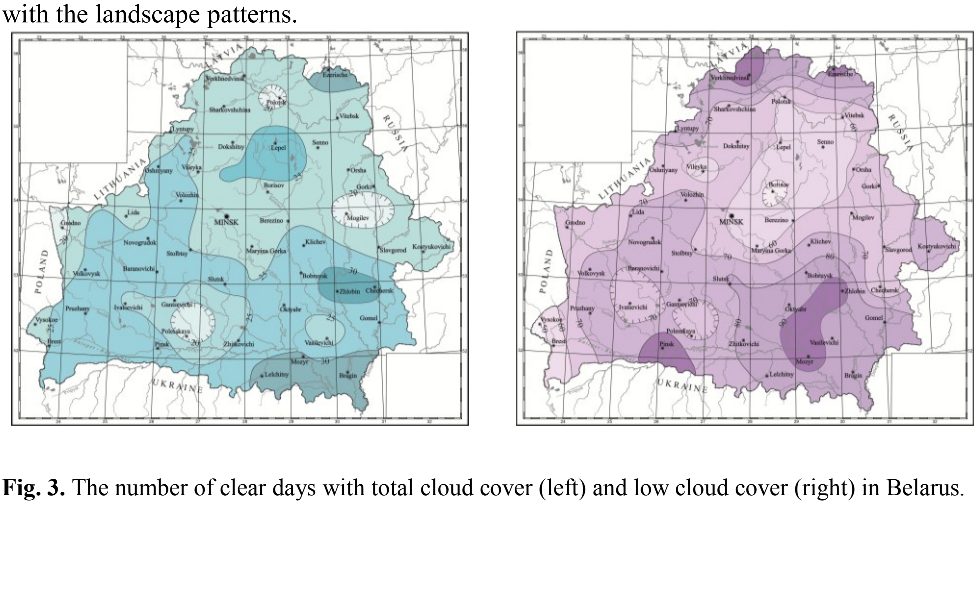


Fig. 3. The number of clear days with total cloud cover (left) and low cloud cover (right) in Belarus.

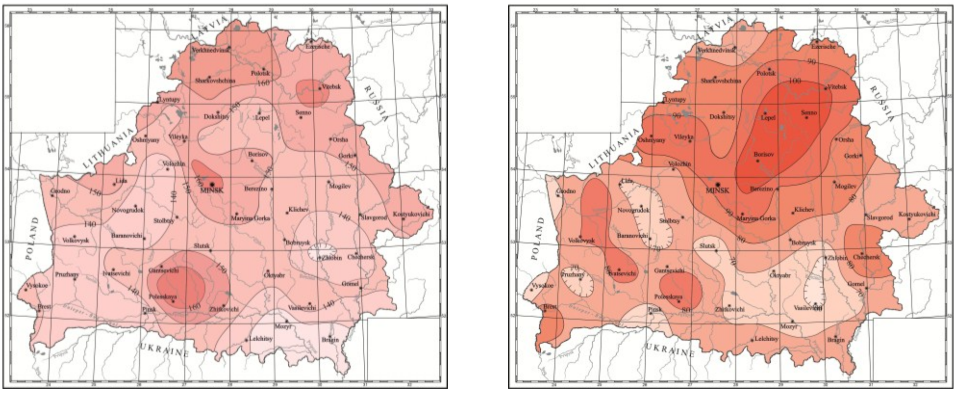


Fig. 4. The number of cloudy days with total cloud cover (left) and low cloud cover (right) in Belarus.

There is a certain correlation between the increase in the average annual duration of sunshine, the number of clear days with total and low cloudiness and decrease in the number of cloudy days with total and low cloud cover from the north, northwest to the south, southeast [4]. Cloudiness reduces the annual amount of total solar radiation by 2.5-3 times. For example, in Minsk, with no cloud cover, the annual amount of solar radiation can reach 4485 MJ / m^2. Annual sums of total radiation are reduced by about 40% compared with what they would be in a clear sky. At the same time, the amount of diffuse radiation under average cloudy conditions is about 40% higher than that in the clear sky [4].

There is a certain correlation between the annual amount of sunshine duration and the average annual cloud cover but their statistical significance is not proved (Fig. 5).

The correlations between the number of clear and cloudy days per year and low cloudiness are statistically significant (Fig. 6).

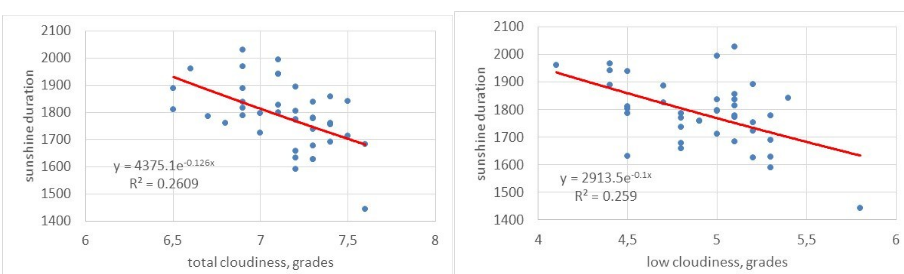


Fig. 5. Dependence of sunshine duration on different types of cloudiness in Minsk.

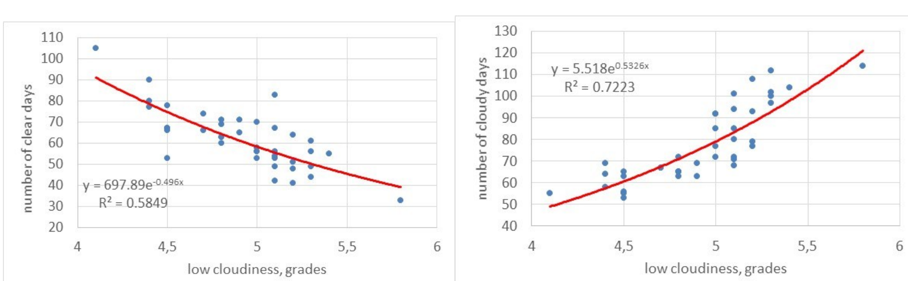


Fig. 6. Dependence of the number of clear and cloudy days on low cloudiness in Minsk.

The research has shown that characteristics of low cloud cover can be a fairly good tool to assess solar energy resources if actinometric data are limited or insufficient.

The intra-annual course of the possible and actual sunshine duration on the territory of Belarus is shown in Fig.7.

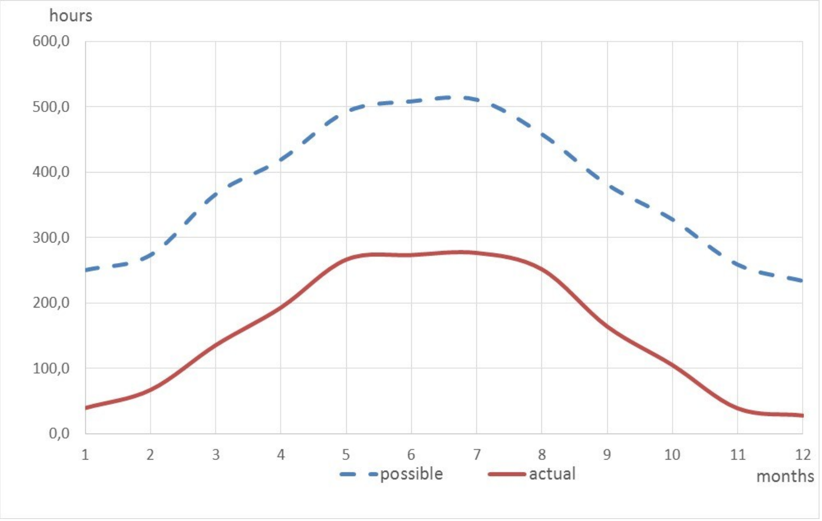


Fig. 7. Possible and actual duration of sunshine in Belarus.

The curves (Fig. 7) follow almost synchronously and allow us to assess the relationship between the actual and possible values of sunshine duration (Table 3).

Thus, Figure 7 shows that the duration of sunshine is minimal in December - February and maximal in May - August. Some researchers [8] state that the optimal efficiency of almost all solar power plants is achieved when the sunshine duration is more than 250 hours per month.

Moreover, it is not the distribution of radiation regime characteristics within a day that matters but their monthly and annual amounts are important to judge about the real solar energy potential. 220-225 hours of sunshine duration per month also allow us to consider the efficiency of solar power facilities satisfactory. This criterion is provided in Belarus from April to September. Sunshine duration of over 250 hours a month is observed from May to August. In particular years, the actual duration of sunshine can exceed 420 hours in July, June but sometimes it decreases to less than one hour in December.

Table 3. The ratio of actual duration of sunshine to the possible one, %.

Month / Meteorological station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Verchnedvinsk	13.5	23.4	36.8	45.7	55.0	53.1	55.5	53.1	40.9	28.5	12.7	10.6	40.5
Minsk	14.7	23.3	36.5	46.0	52.3	52.3	52.3	53.6	42.3	30.0	15.1	10.7	39.9
Brest	16.9	24.8	36.7	45.9	53.9	53.4	54.1	56.7	44.7	36.9	18.6	14.5	41.8
Homel	18.1	27.8	39.2	46.8	57.5	56.3	56.3	57.5	46.4	34.9	16.2	13.1	43.3
Vasilevichi	17.5	26.2	37.5	47.3	56.8	56.2	56.8	57.8	45.7	34.6	15.2	12.5	47.3

The longest actual duration of sunshine corresponds to the summer months. It reaches its maximum (277 hours) in July and decreases to 28 hours in December. In May-August period, the actual sunshine duration exceeds 50% of the possible one and it is less than 15%

in December-January. This distribution is predetermined by the cloudiness pattern in these months (Fig. 1). On average, the ratio of the actual and possible sunshine duration is about 40% within a year and it differs insignificantly around Belarus. In some months of the cold season territorial differences increase. They are connected with the latitude.

The amount of solar radiation is predetermined by the geographic location of Belarus and depends on the sunshine duration and cloud cover pattern as well as on the height of the sun above the horizon at different time of the year. The longest day is 2.5 times longer than the shortest one in the north of Belarus and it is 2.1 times longer in the south. The difference in the day length is about one hour both in the north and south, both in summer and in winter. The day in the north of Belarus in summer is longer than in the south but the sun is lower; this somewhat reduces the differences in climatic conditions between the southern and northern regions. In winter, when both the length of the day and the height of the sun's standing above the horizon in the south are greater than in the north, the south is in more favourable conditions than the north [24].

Possible sunshine duration in Belarus is 4495 ± 10 hours per year. It is longer in the north due to refraction. Therefore, differences in the actual sunshine duration are determined by the cloud cover pattern. The average annual duration of sunshine increases from the north, northwest to the south, southeast by about 7%: from 1740 hours (Lida, Oshmyany) to 1870 hours (Bragin) (Fig. 8) [22].

Figure 8 coincides with the state cadastre of renewable energy sources where the territory is zoned according to the possibilities for practical implementation of solar energy potential.

There is an increase in the annual sunshine duration at all meteorological stations around Belarus by 46 hours over 10 years on average (from 20 hours in Verkhnedvinsk to 77 hours in Oshmyany) (Fig. 9). This suggests that climatic conditions to develop solar energy are becoming more favourable. A significant increase in the annual values of sunshine duration in Moscow is also noted in the work [25] with a trend of about 35 hours over 10 years.

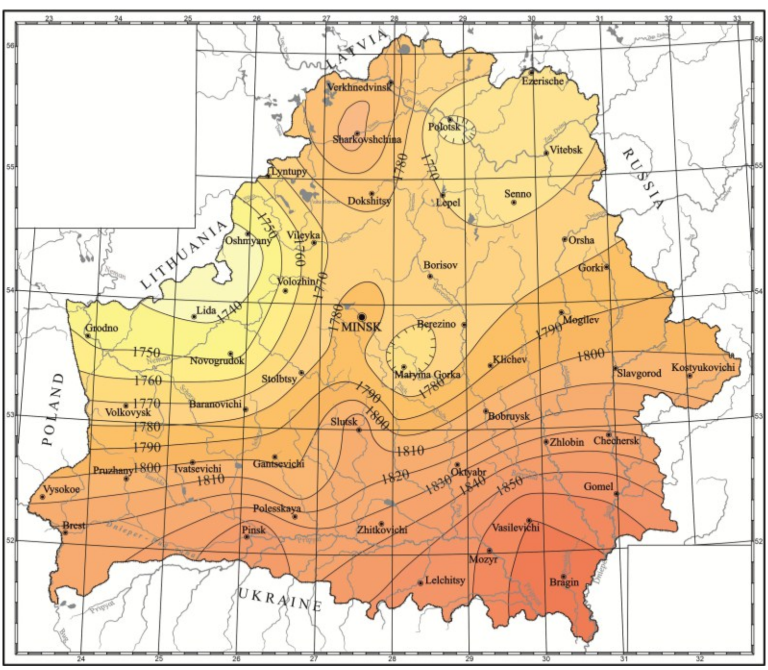


Fig. 8. Sunshine duration in Belarus, hours per year.

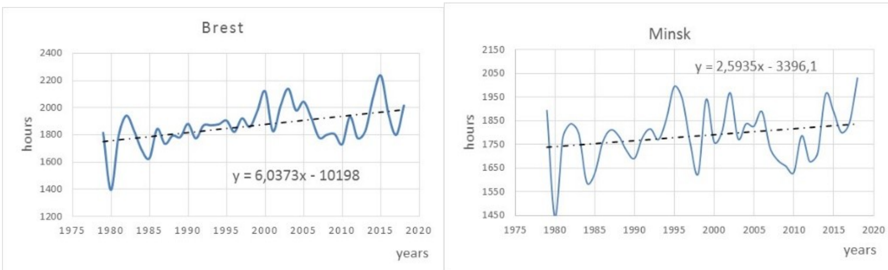


Fig. 9. Time variability of sunshine duration in Belarus.

Figure 10 shows time variability of sunshine duration in Minsk in particular months. We observe a positive trend in most months of the year with the largest one in September and June. However, there is a decrease in monthly sunshine duration in February, October, November, and December. Such trends are observed at all meteorological stations in Belarus. They result from a change in the pattern of atmospheric circulation.

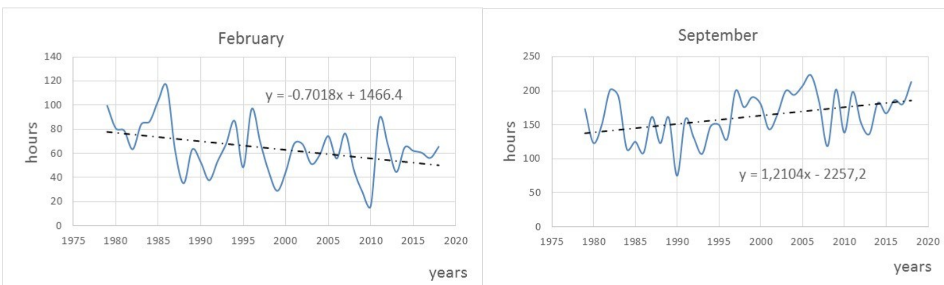


Fig. 10. Time variability of sunshine duration in Minsk (per months and per year), in hours

4 Conclusion

At present, a surplus of electricity is predicted in Belarus due to developing nuclear power and commissioning the first Belarusian nuclear power plant. Nevertheless, it is necessary to diversify our energy sources. This will strengthen the country's national security and reduce dependence on external factors, minimize market risks and energy failures. Currently, the dependence on imported hydrocarbons is great, that is why we need to develop alternative "green" energy which will also contribute to environmental safety.

The results obtained in this research allow us to conclude that there are enough solar energy resources in Belarus to develop solar power industry but they are distributed unevenly throughout the year. Our analysis of time series of observations over cloudiness patterns, sunshine duration, total solar radiation and its intensity over a 40-year period from 1979 to 2019 revealed that the most productive period for operating solar power plants is the period from February to November. In December and January, total solar radiation does not reach 0.60 kW / m^2, so generating electricity by solar power facilities is impractical. Since the number of meteorological stations that register actinometric data is limited in Belarus, the researchers have to apply analytical calculation methods to determine relationships between total solar radiation, its intensity and other widely observed parameters such as cloud cover, sunshine duration, etc.

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