

## Analysis of the Radiation Regime of the Atmosphere for the Assessment of Potential Solar Energy Resources of Ukraine

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### ABSTRACT

**Problem Statement.** Solar energy is steadily gaining a strong foothold in global energy systems. Solar energy is accessible in every corner of our planet, differing in radiation density by no more than a factor of two. Moreover, solar energy is an environmentally clean energy source, enabling its use on an ever-increasing scale without adverse effects on the environment. Solar energy is also an almost inexhaustible source of energy, available even millions of years from now. Thanks to the development of solar installation designs, which are economically viable in certain physical-geographical areas, the prospects for utilizing radiant energy from the Sun have become more tangible. However, this requires researchers to conduct detailed studies of the energy resources of specific regions of the globe to assess their energy potential thoroughly.

**The purpose** of this article is to identify the characteristics of the atmospheric radiation regime to evaluate Ukraine's solar energy resources.

**Methodology.** The utilization of solar energy primarily depends on the geographical location of the area, and the level of solar radiation determines the efficiency of solar installations. Therefore, analyzing the prospects for using solar radiation in various regions of Ukraine based on their geographical location, cloudiness, and season is essential. Solar energy inflow across Ukraine should be studied not individually by regions but grouped by the geographical position of the regions in degrees of northern latitude. To assess the potential solar energy resources of a given area, justify the technical-design parameters of various solar systems, and evaluate the economic feasibility of their operation across different seasons and times of day at specific locations, the following indicators are needed: potential sums of direct, diffuse, and total solar radiation, sunshine duration (number of hours), average cloud cover indicators, number of clear and cloudy days. The research includes an analysis of total solar radiation sums under various sky conditions and sunshine duration for Ukrainian regions over different periods. Meteorological stations across different regions of the country were selected to achieve the study's objectives.

**Results.** The analysis of total radiation flows over the territory of Ukraine for different periods and under various sky conditions shows that the maximum sums are typical for Odesa, while the minimum values are observed in Kovel. The annual distributions have a clearly defined pattern, with peaks in June and July. The sums of total radiation differ under various sky conditions across regions: in summer, these changes range between 10–30 %, while in winter, the values may vary 1.5 to 2.5 times, particularly during the 1991–2020 period. Annual sums of total radiation are generally lower during the 1961–1990 period. The analysis of sunshine duration demonstrates that the highest figures are characteristic of Odesa. The annual curves have a similar structure across different periods at all stations, with peaks in June–July and lows in December.

**Novelty and Practical Significance.** The study analyzed two indicators of the atmospheric radiation regime – total solar radiation inflow and sunshine duration across different climatic periods. The findings of the research highlight that Ukraine's energy potential is promising for supporting the fuel-energy sector and the further development of the country's solar energy industry.

**Keywords:** *total solar radiation, sunshine duration, solar energy resources, alternative energy, annual indicators, long-term distribution, climate normals, solar radiation under clear sky conditions, solar radiation under average cloud cover conditions.*

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**Problem Statement.** The major challenges that humanity faced entering the 21st century are energy and ecology. The rapid industrial development of a group of countries in the Northern Hemisphere was fueled by the intensive growth in the production of electricity and thermal energy. Over the past 150 years, since the mid-19th century, the Earth's population has grown fivefold, while energy production has increased twenty-one times. According to expert estimates by the International Energy Agency, the production of primary energy globally will grow annually by an average of 1.7% until 2030 [1, 2]. At

the same time, it is assumed that more than 90% of this growth in energy production will rely on fossil fuels. The ever-increasing volumes of its use lead to higher CO<sub>2</sub> emissions and other greenhouse gases into the atmosphere, negatively affecting the planet's climate. Moreover, reserves of fossil fuels, particularly easily accessible ones such as oil and gas, are fairly limited. Various assessments suggest that significant depletion could occur by the mid-21st century. Meanwhile, our planet has practically inexhaustible (in the context of human history) renewable energy sources, primarily including solar energy,

wind, rivers, and biomass [1].

Solar energy is steadily securing a strong position in the global energy sector. Its appeal is determined by several factors. Solar energy is available at every point on our planet, differing in radiation flux density by no more than two times. This makes it attractive to all countries as it aligns with their interests in achieving energy independence. Solar energy is an environmentally clean source that allows for expanding use without causing negative effects on the environment. Moreover, it is a virtually inexhaustible energy source that will remain accessible even in millions of years [1].

Currently, the development of solar power system designs, whose operation is economically feasible in certain physico-geographical regions, has made the prospects of utilizing solar radiant energy more tangible. However, this, in turn, requires researchers to conduct a detailed study of the energy resources of specific regions of the globe to determine their energy potential.

#### **Analysis of Recent Studies and Publications.**

The primary energy source that sustains life on Earth is the Sun, whose energy reaching our planet annually exceeds the energy of all extracted reserves of fossil fuels by 10 to 20 times. This explains the global community's attention to utilizing solar energy, particularly in industrially developed countries [1].

Forecasts for the development of renewable energy sources over the longer term (by 2050), based on current growth rates of energy equipment capacity, indicate that the share of such sources in electricity production in EU countries could approach up to 50 %. This would make a significant contribution to improving the planet's ecology, reduce the anthropogenic impact on the climate, and create conditions for the continued sustainable development of our civilization [3].

Modern global energy systems, including them in Ukraine, are predominantly based on non-renewable energy sources. Due to their limited reserves, these sources are finite and cannot ensure sustainable energy development over the long term. Additionally, their use is one of the primary factors contributing to environmental degradation. Significant attention is being given to the development of alternative, unconventional renewable energy sources. In Ukraine, the share of alternative energy sources in the total energy consumption does not exceed 0.7%. This is despite the adoption of the "Energy Strategy of Ukraine until 2030" by the Cabinet of Ministers on March 15, 2006, which aims to increase the share of alternative energy sources up to 19% of the country's total fuel and energy balance by 2030 [2]. Under current conditions, Ukraine, as an energy-deficient country, faces the urgent task of developing alternative energy. The primary advan-

tages of alternative energy over traditional non-renewable sources include practically inexhaustible resources and reduced environmental impact, such as lower emissions of pollutants, greenhouse gases, radioactive and thermal pollution, etc.

Solar energy is a type of renewable energy in which electricity is generated using solar radiation [4]. The use of solar energy not only helps preserve the Earth's climate but also reduces countries' dependence on imported hydrocarbons. The amount of solar energy is reaching the Earth's surface in one week exceeds the energy of the world's reserves of oil, gas, coal, and uranium combined. Humanity utilizes only one ten-thousandth of this type of energy. Scientists are confident that if humans utilized even 1 % of solar energy, the energy crisis would be in the past [1]. In Ukraine, several dozen experimental projects have been implemented in various sectors of the national economy. They include systems for hot water supply in residential and public buildings, as well as in healthcare facilities; solar collector systems integrated with fuel and electric boiler plants serving industrial, agricultural, and municipal enterprises; and small autonomous installations for individual households and consumer service enterprises. A significant potential for using solar energy in Ukraine lies in employing it for cooling and air conditioning, as well as in agricultural applications, such as drying various types of agricultural products and desalinating water in southern regions [5-11].

Alternative energy is designed to help solve, first of all, two important problems – environmental safety and energy efficiency. The issue of energy efficiency of alternative fuels in Ukraine is the most relevant than in the world. The efficiency of solar installations is primarily influenced by the level of solar energy, which in turn depends on the geographical location of the territory [1].

**Identification of Previously Unresolved Aspects of the General Problem.** In recent years, a significant number of scientific and practical works have been published, addressing the efficient use of solar energy [1, 5, 12, 13]. The prospects for replacing traditional fuel and energy resources with alternative energy sources are presented in academic works [14, 15]. But most of these studies focus on the efficiency and rational use of renewable energy sources, while the issue of their potential remains underexplored. Analytical and experimental studies of the distribution of solar energy throughout the day and year are presented in the monograph [16], but it does not include data on the amount of solar energy reaching Ukraine's territory. Climatic data used for the calculation and design of solar power systems are provided in the State Building Standards of Ukraine [17]. However, these standards do

not account for the seasonal solar energy amounts depending on geographic latitude.

**The purpose** of the article is to identify the characteristics of the radiation regime of the atmosphere to assess the solar energy resources of Ukraine.

#### Presentation of the Main Research Material.

Assessing the energy potential of solar energy is a crucial factor in selecting the location for solar installations. The efficiency of solar systems depends on the level of solar energy, which, in turn, is influenced by geographical latitude. The operating mode of solar energy installations is determined by a set of heliophysical parameters needed to utilize their energy potential with specific characteristics. These characteristics account for the chronological steady course of solar radiation and its random variability over time, caused by various atmospheric phenomena. To evaluate the feasibility of solar energy installations, specialized indicators of climatic resources are used [1, 13, 18, 19]. The utilization of solar energy primarily depends on the geographical location of the area, while the level of solar radiation determines the efficiency of solar installations. Therefore, analyzing the prospects for solar radiation usage in different regions of Ukraine, based on their geographical location, cloud cover, and seasonal variations, is essential. According to the State Building Standards, it is advisable to analyze the inflow of solar energy into the territory of Ukraine not separately by region, but by combining them according to the geographical location of the regions in degrees of northern latitude. To determine the potential solar energy resources of a particular area, justifi-

fy technical design parameters of various solar systems, and assess their economic efficiency during different seasons and times of the day at a specific location, a set of indicators is required. These include values of possible sums of direct, diffuse, and total solar radiation; the number of sunshine hours (duration of sunshine); average cloud cover indices; and the number of clear and cloudy days.

The article presents an analysis of total solar radiation values under different sky conditions and sunshine durations for various regions of Ukraine across different time periods. To achieve the research objective, meteorological stations in specific regions of the country were selected: Kovel in northwestern Ukraine, Odesa in southwestern Ukraine, Poltava in central Ukraine, and Pokoshychi in northern Ukraine. The research periods cover 1951-1963 [20], 1961-1990 [21], and 1991-2020 [22].

In Fig. 1, the sums of total solar radiation under clear sky conditions at the Pokoshychi station are presented. The distributions exhibit a distinct annual pattern, with minimum values in December and maximum values in June across all periods. The highest sums under clear sky conditions at the station were observed during the period of 1991-2020. In November and the winter season, the values are lower compared to other periods, while from March to August, the highest values are recorded during this period. In September, the values for 1961-1990 and 1991-2020 are identical, at 494 MJ/m<sup>2</sup>, whereas for 1951-1963, the sums are greater than in the other periods, reaching 499 MJ/m<sup>2</sup>. In October, November, and December, the total solar radiation sums are also the highest during the 1991-2020 period.

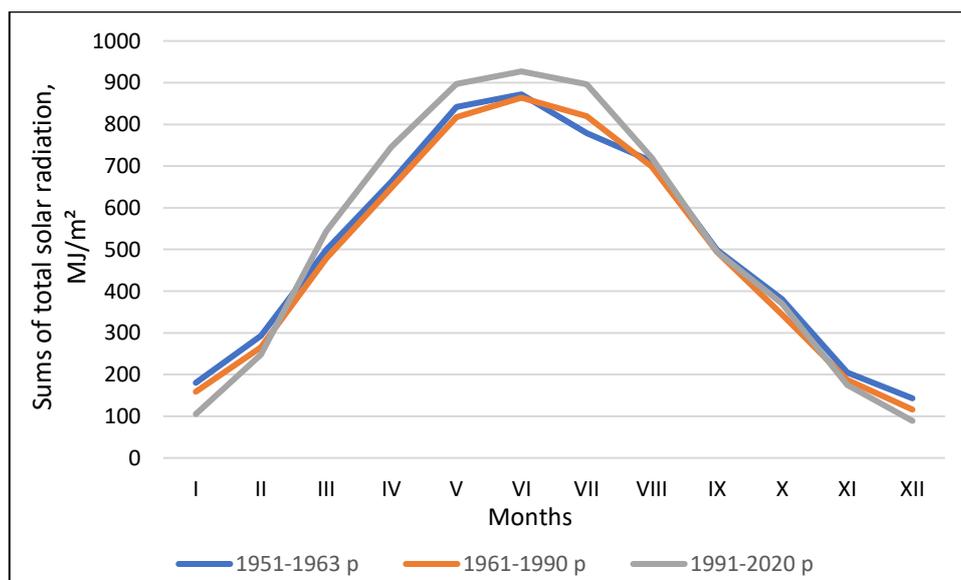


Fig. 1. Sums of total solar radiation (MJ/m<sup>2</sup>) under clear sky conditions at the Pokoshychi Station

The highest sums of total solar radiation under clear sky conditions at the Kovel station across different periods (Fig. 2) were observed during the

1951-1963 period, with a maximum value of 918 MJ/m<sup>2</sup>. Slight differences were noted in February between the 1951-1963 and 1961-1990 periods,

with values of 268 MJ/m<sup>2</sup> and 262 MJ/m<sup>2</sup>, respectively. The 1991-2020 period stands out with the lowest total radiation values throughout the year, except in August, when a maximum of 912 MJ/m<sup>2</sup> was recorded, surpassing all other periods. It is noteworthy that in the summer season, the curve exhibits a slight wave pattern, with a minimum in July and peaks in June and August, which is atypical for the distribution of total radiation flows.

The annual distribution of total solar radiation

sums under clear sky conditions at the Poltava station (Fig. 3) indicates that the highest values during May, June, July, and August were observed in the period from 1991 to 2020. In the autumn and winter seasons, the 1951-1963 period demonstrated higher values, albeit with minor differences compared to other periods. The maximum sum for the Poltava station is 948 MJ/m<sup>2</sup>, recorded during the 1991-2020 period. It is noteworthy that the lowest total radiation flows occurred during the 1961-1990 period

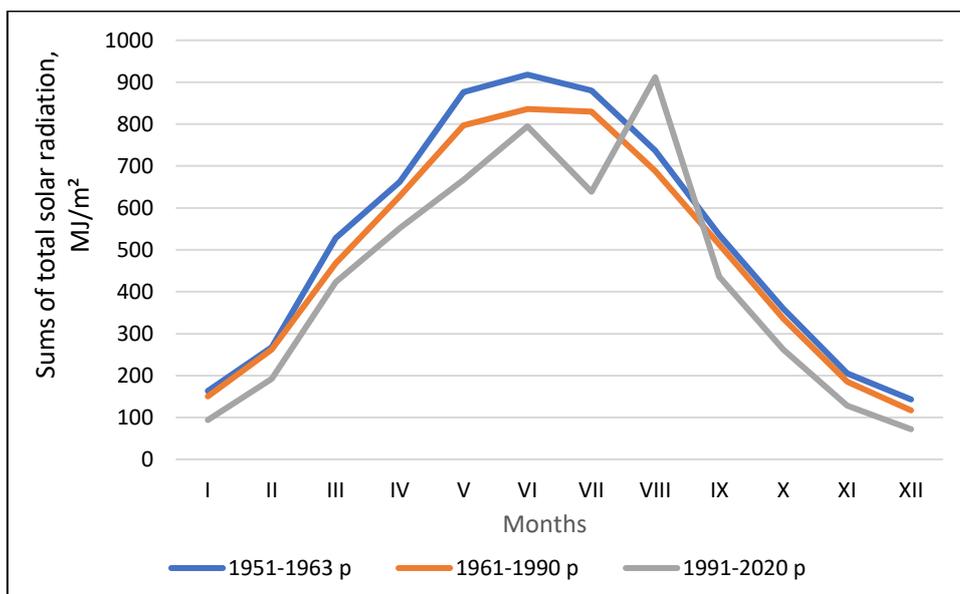


Fig. 2. Sums of total solar radiation (MJ/m<sup>2</sup>) under clear sky conditions at the Kovel Station

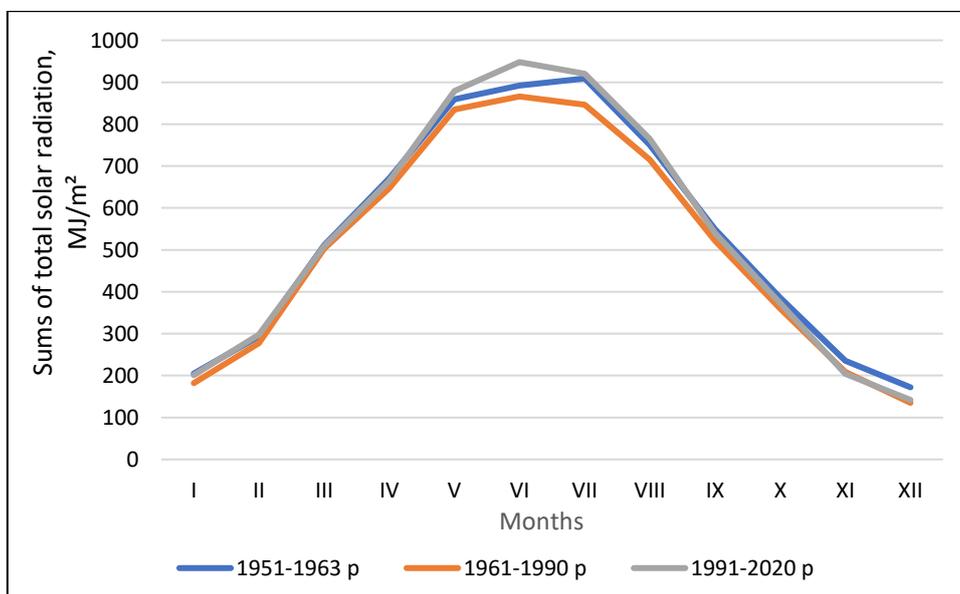


Fig. 3. Sums of total solar radiation (MJ/m<sup>2</sup>) under clear sky conditions at the Poltava station

throughout the annual distribution.

The results for the Odesa station (Fig. 4) indicate that the highest sums of total solar radiation under clear sky conditions were recorded during the 1951-1963 period. The maximum value for this period is 913 MJ/m<sup>2</sup>, observed in June. The lowest radiation flows were noted during the 1961-1990

period across the annual distribution. Overall, a small difference in quantitative indicators throughout the year can be observed between the 1951-1963 and 1991-2020 periods.

As is known, solar radiation flows depend on sky conditions. Therefore, the next task of the study is to analyze the annual distribution of total solar

radiation sums under average cloud cover conditions. The results of the calculations are presented in Figures 5-8.

At the Pokoshychi station (Fig. 5), the highest sums of total solar radiation under average cloud cover conditions were observed during the 1991-2020 period, except for the winter months and November. In these months, the values were higher

during the 1951-1963 period. From the figure, it is evident that the values for the 1951-1963 and 1961-1990 periods are nearly identical, except in July. Additionally, it is noteworthy that the peak in July was recorded only during the 1951-1963 period, while in other periods, it occurred in June. The highest value for the Pokoshychi station is 683 MJ/m<sup>2</sup>, recorded in June 1991-2020.

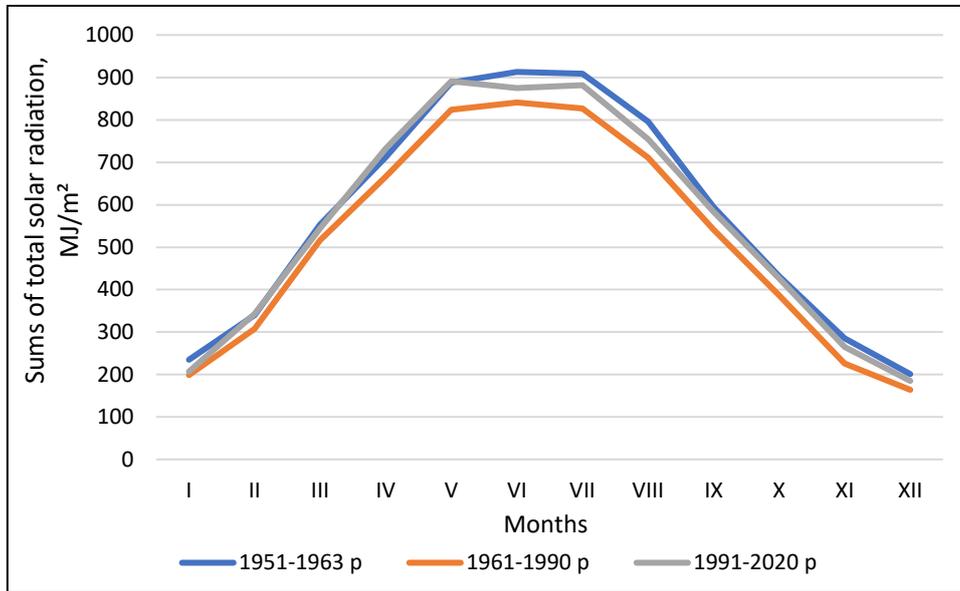


Fig. 4. Sums of total solar radiation (MJ/m<sup>2</sup>) under clear sky conditions at the Odesa station

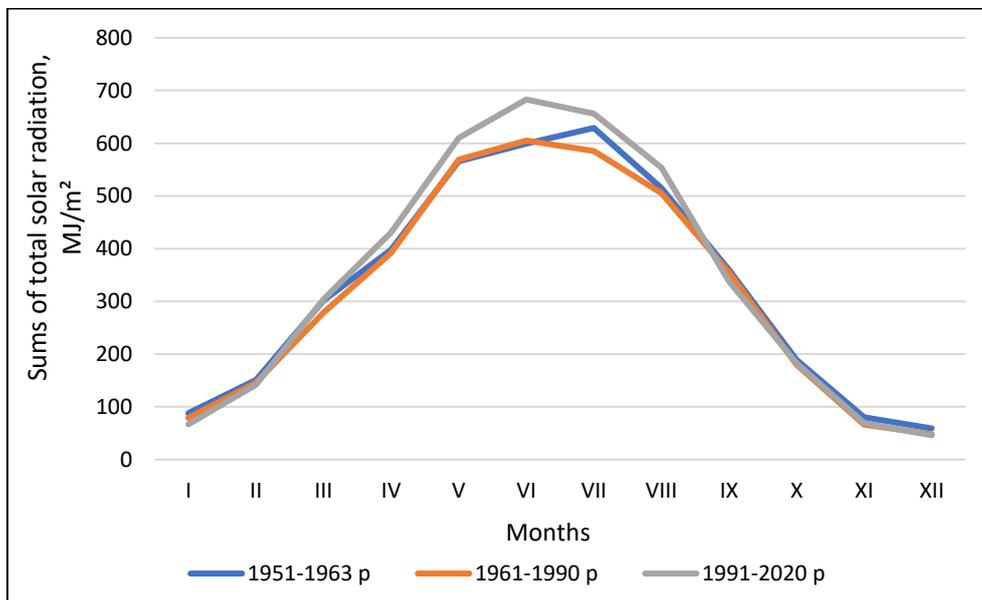


Fig. 5. Sums of total solar radiation (MJ/m<sup>2</sup>) under average cloud cover conditions at the Pokoshychi Station

At the Kovel station (Fig. 6), the highest sums of total solar radiation under average cloud cover conditions were observed during the 1951-1963 period. The annual distribution shows that values across the three periods in January, February, November, and December are nearly identical. The highest recorded value for the station is 615 MJ/m<sup>2</sup> in June during the 1991-2020 period, with a slight

difference of 612 MJ/m<sup>2</sup> in the 1951-1963 period. In August 1991-2020, a unique peak was recorded, which is absent in the other periods.

At the Poltava station (Fig. 7), the highest sums under average cloud cover conditions were found during the 1991-2020 period. The distribution indicates minimal differences in values across the three periods for January, February, March, November,

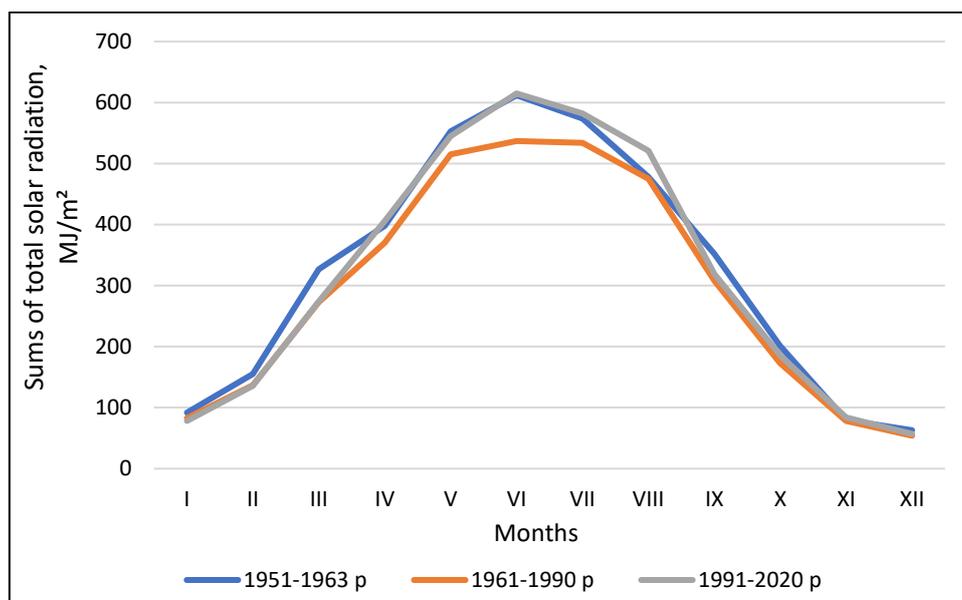


Fig. 6. Sums of total solar radiation (MJ/m<sup>2</sup>) under average cloud cover conditions at the Kovel Station

and December. The maximum value for the station is 699 MJ/m<sup>2</sup> in June. For the 1951-1963 and 1961-1990 periods, the values are approximately equal, except during the summer season, where the peak shifted by one month from June in 1961-1990 to July in 1951-1963.

At the Odesa station, there are no differences in the annual distribution of total solar radiation sums between the periods 1951-1963 and 1991-2020 (Fig. 8). The highest sums were observed in the 1951-1963 period, with the maximum value reaching 758 MJ/m<sup>2</sup> in July. The same month also recorded a peak of 731 MJ/m<sup>2</sup> during the 1991-2020 period. From March to September, the sums of total radiation in the 1961-1990 period are the lowest compared to the other periods. Quantitative indicators for January, February, September, November, and December are

nearly identical across all periods.

It is appropriate to analyze the long-term sums of total solar radiation (Fig. 9-10). The highest quantitative indicators are recorded at the Odesa station under various sky conditions. In other cases, the histograms do not differ significantly, except for the data at the Kovel station. Here, the radiation sums under clear sky conditions are highest during the 1951-1963 period and gradually decrease over subsequent periods. In Poltava, by contrast, the annual sums increase from the first to the third period. At the Pokoshychi and Odesa stations, a certain oscillatory pattern is observed, with a minimum in the second period. Under average cloud cover conditions, a similar distribution of total radiation sums is observed across stations, except for Poltava, where the annual sums increase consistently from the first

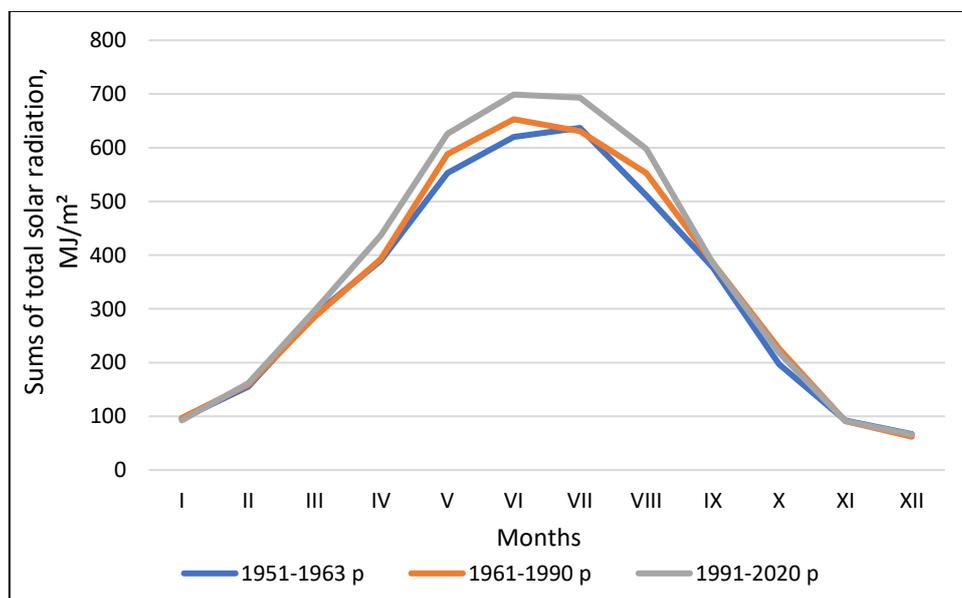


Fig. 7. Sums of total solar radiation (MJ/m<sup>2</sup>) under average cloud cover conditions at the Poltava Station

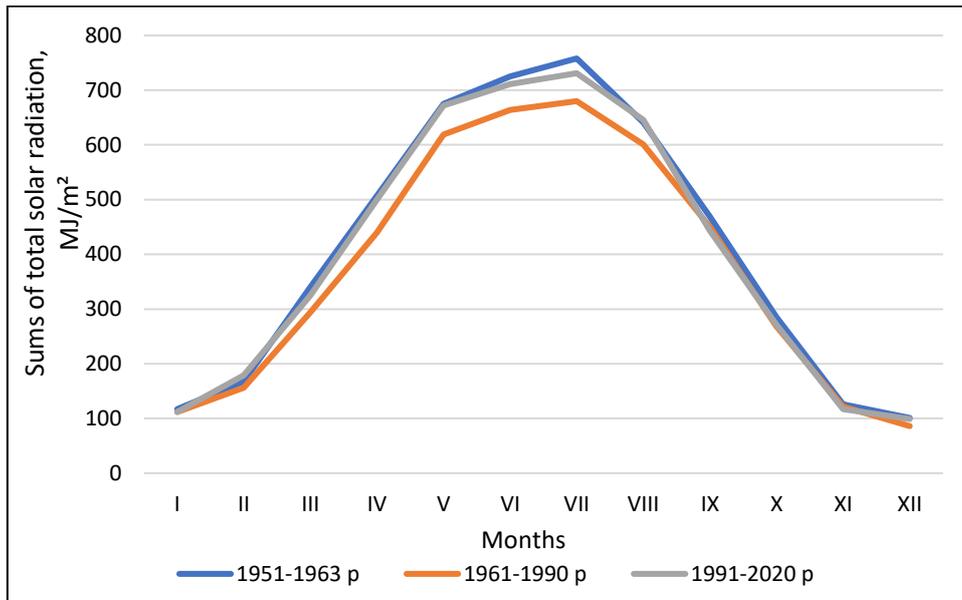


Fig. 8. Sums of total solar radiation (MJ/m<sup>2</sup>) under average cloud cover conditions at the Odesa Station

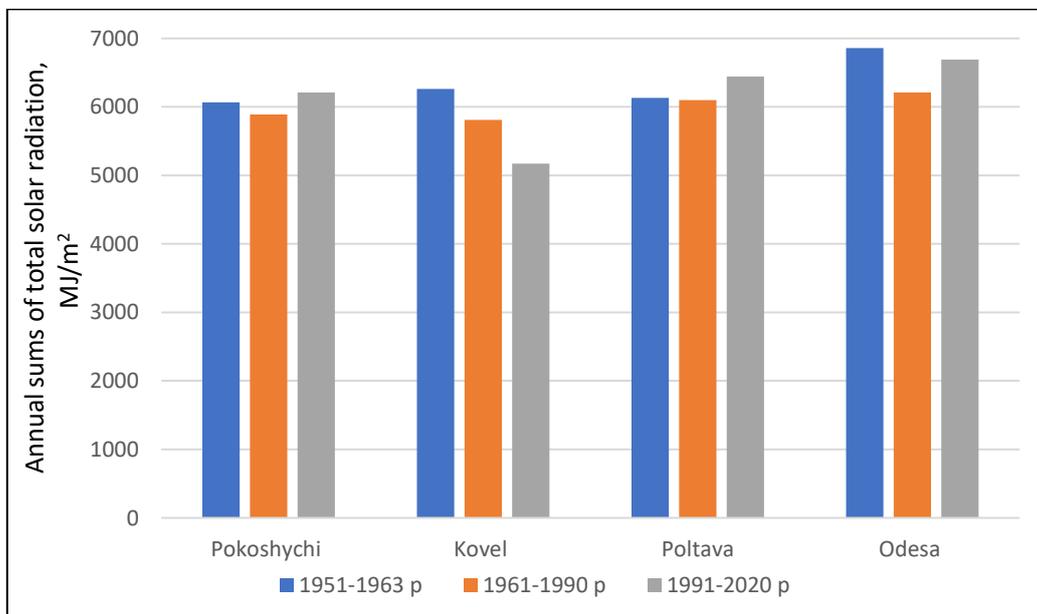


Fig. 9. Long-term sums of total solar radiation under clear sky conditions, MJ/m<sup>2</sup>

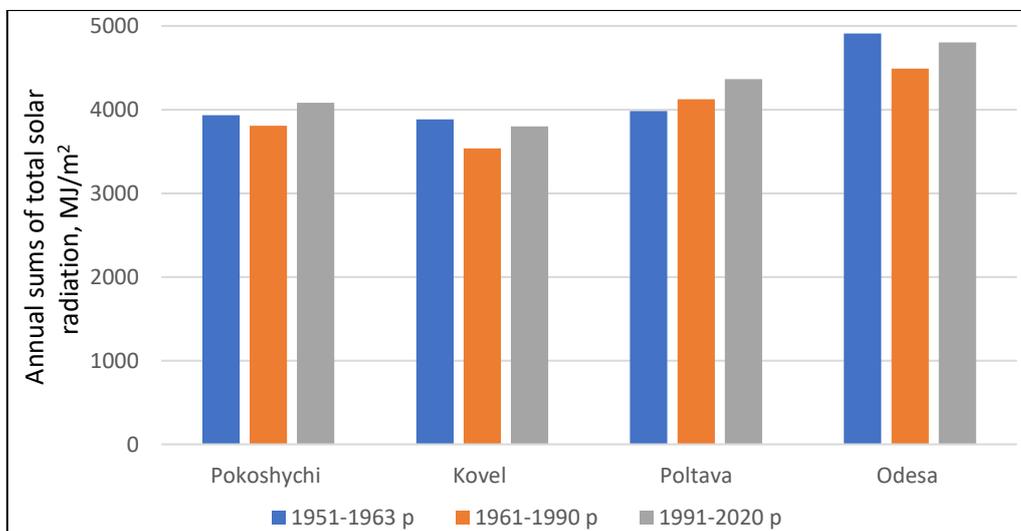


Fig. 10. Long-term sums of total solar radiation under average cloud cover conditions, MJ/m<sup>2</sup>

to the third period.

As mentioned earlier, one of the key characteristics of the radiation regime is the duration of sunshine. The heterogeneity of the underlying surface creates a mosaic pattern in the distribution of sunshine duration in mountainous regions. Due to anthropogenic activities, such as urbanization and large industrial complexes, atmospheric pollution reduces the number of sunshine hours. Throughout Ukraine, annual sunshine duration ranges from less than 1600 hours in the northwest to over 2300 hours in the southern regions of the Crimean Peninsula [23]. December marks the minimum values for the entire country, as the shortest daylight hours and a high probability of cloudy skies are characteristic of this month. Starting in March, the increase in daylight duration (approximately from 8 hours in December to 12 hours in March) and the noticeable decrease in cloudiness lead to a significant rise in sunshine duration from the Polissia to the steppe zones. The monthly maximum duration is reached in July, determined by the longest daylight hours and the highest number of clear and partly clear days compared to other months [1].

Continuous sunshine duration, which minimizes energy consumption for heating solar installations, according to B. N. Vanberg, should exceed 6 hours per day. Across most of Ukraine, this value is surpassed during the radiation-warm period (April-September), ranging from 6.5 hours in April and September in the northwest and northeast, increasing southward: from 6.5 hours in April to 7-8 hours in September. The highest values are observed in summer, especially in June, when daily sunshine duration increases to 9-10 hours, starting from the northern regions. The exception is the mountainous areas of the Ukrainian Carpathians, where this value

slightly increases in summer months (up to 7 hours). However, during certain years, the minimum values in these regions can be almost half of the required level [1, 24].

In Figure 11, the duration of sunshine at the Pokoshychi station is presented for different periods. The longest duration is observed in June during the 1991-2020 period, reaching 298 hours. During the 1951-1963 period, the distribution shows two peaks in May and July, distinguishing this period from others. In December, the values for both the 1991-2020 and 1951-1963 periods are identical at 23 hours, while in February, the duration is 66 and 65 hours, respectively. For the 1961-1990 period, the February duration is 27 hours. During the summer season, the quantitative values for the 1961-1990 period are the lowest.

At the Kovel station (Fig. 12), the highest sunshine duration is recorded in July during the 1991-2020 period, reaching 272 hours. Overall, the values during this period are greater compared to other periods throughout the spring and summer seasons. In October, the values across all periods are similar: 124 hours for 1951-1963, 120 hours for 1961-1990, and 119 hours for 1991-2020. During the winter season, the maximum duration is observed in the 1961-1990 period. At the Poltava station (Fig. 13), the annual sunshine durations across all periods are generally similar. The largest difference is observed in April. Winter and summer season peaks are recorded during the 1961-1990 period. Throughout spring, the highest values are found during the 1991-2020 period. The maximum sunshine duration is observed in June during the 1961-1990 period, reaching 299 hours. However, the difference compared to other periods is not significant: 293 hours for 1951-1963 and 292 hours for 1991-2020.

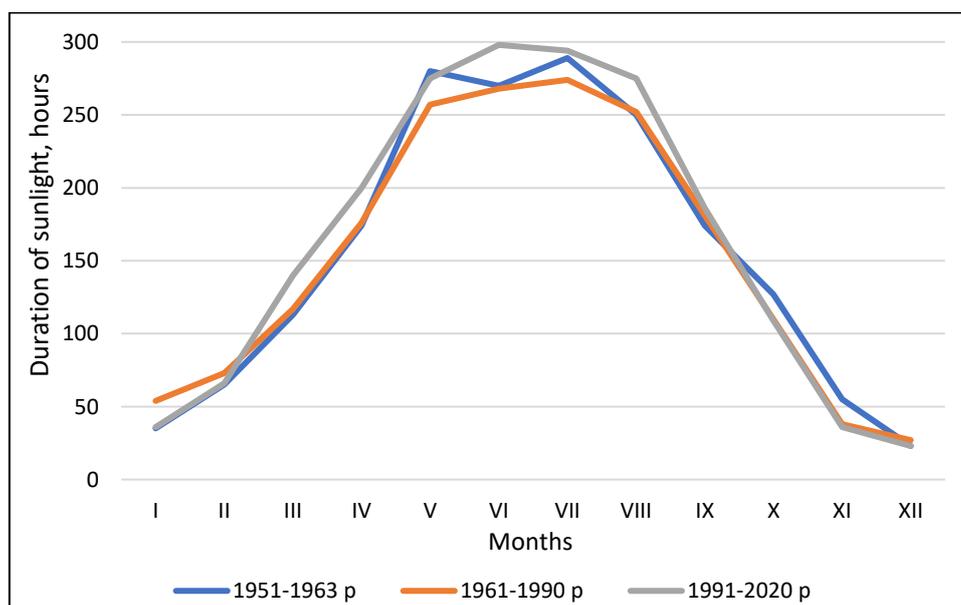


Fig. 11. Duration of sunlight at Pokoshychi Station, hours

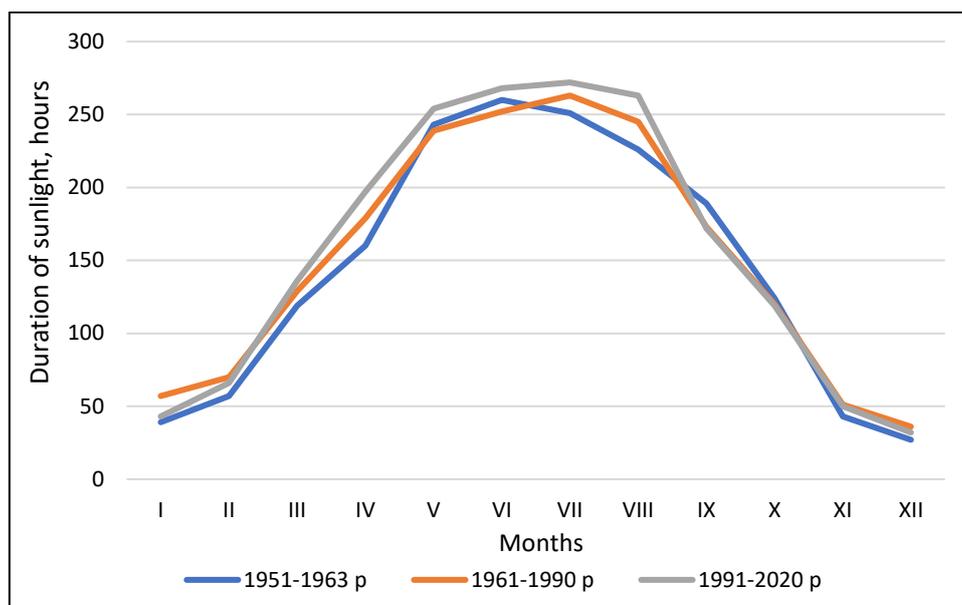


Fig. 12. Duration of sunlight at Kovel Station, hours

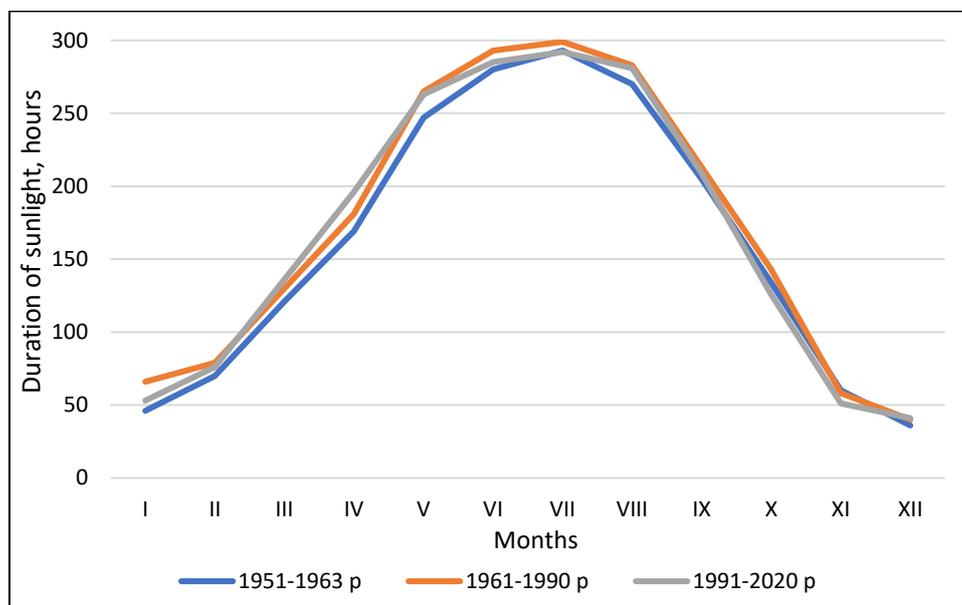


Fig. 13. Duration of sunlight at Poltava Station, hours

It is evident that in Odesa (Fig. 14), the sunshine duration is the highest compared to other stations. The maximum value is recorded in June during the 1951-1963 period, reaching 349 hours, while for the 1991-2020 period, the duration is 348 hours.

In autumn, the quantitative indicators for all periods are similar. During spring and summer, the minimums were recorded for 1961-1990, the maximums for the period 1991-2020.

**Conclusions.** Analysis of the total radiation fluxes on the territory of Ukraine for different periods under different sky conditions shows that the maximum amounts are characteristic of Odesa, the minimum - for Kovel. Annual distributions have a clearly expressed character with a maximum in June and July. The total radiation amounts differ under

different sky conditions for different regions: in summer, these changes fluctuate within 10-30%, in winter these indicators can change by 1.5-2.5 times, especially in the period 1991-2020. The annual total radiation amounts are generally lower in the period 1961-1990. Analysis of the duration of sunshine shows that the highest indicators are characteristic of Odesa. The annual flow curves have a similar structure for different periods for all stations with peaks in June-July and lows in December.

In this work were analyzed two key indicators of the atmospheric radiation regime – total solar radiation sums and sunshine duration. The findings highlight that Ukraine's energy potential is promising for supporting the fuel-energy sector and advancing the development of the country's solar ener-

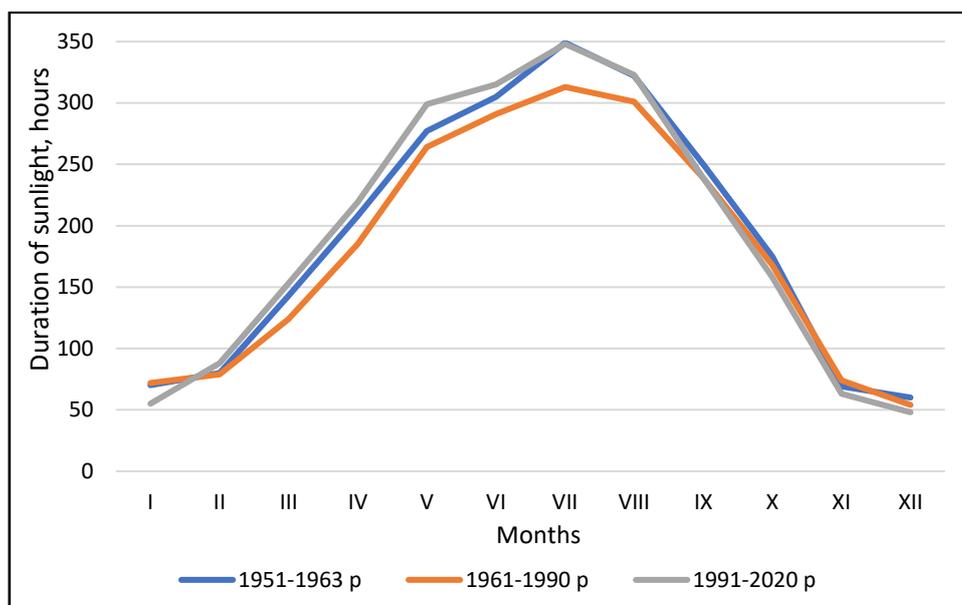


Fig. 14. Duration of sunlight at Odesa Station, hours

gy industry. For more substantiated conclusions, an analysis of average cloud cover indicators and the number of clear and cloudy days is necessary. This

will serve as the next step in researching the atmospheric radiation regime to evaluate Ukraine's solar energy resources more comprehensively.

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## **Аналіз радіаційного режиму атмосфери для оцінки потенціальних геліоенергетичних ресурсів України**

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Сонячна енергія впевнено завойовує стійкі позиції у світовій енергетиці. В теперішній час завдяки розробці конструкцій геліоустановок, експлуатація яких в окремих фізико-географічних районах економічно доцільна, перспективи використання променистої енергії Сонця стали більш конкретними. Але це в свою чергу потребує від дослідників детального вивчення енергетичних ресурсів окремих регіонів Земної кулі для встановлення їх енергетичного потенціалу. Метою статті є виявлення особливостей радіаційного режиму атмосфери для оцінки геліоенергетичних ресурсів України. Використання сонячної енергії залежить, насамперед, від географічного положення території, а від рівня сонячної радіації буде залежати ефективність сонячних установок. Тому необхідно проаналізувати перспективність використання сонячної радіації у різних областях території України залежно від їх географічного розташування, хмарності та періоду року. Для визначення потенційних геліоенергетичних ресурсів тієї чи іншої території, обґрунтування техніко-конструкторських показників різних геліосистем, оцінки економічної ефективності їх експлуатації у різні сезони року і різний час доби в певному місці, необхідно мати набір показників сонячного кадастру. В дослідженні представлено аналіз величин сумарної сонячної радіації за різних умов стану неба та тривалості сонячного сьйва для регіонів України за різні періоди. Для досягнення мети обрано метеорологічні станції в різних регіонах країни. Аналіз потоків сумарної радіації на території України за різні періоди за різних умов стану неба показує, що максимальні суми є характерними для Одеси, мінімальні – для Ковеля. Річні розподіли мають чітко виражений характер з максимумом в червні та в липні. Суми сумарної радіації відрізняються за різних умов стану неба для різних регіонів: влітку ці зміни коливаються в межах 10-30 %, взимку ці показники можуть змінюватися в 1,5-2,5 рази, особливо в період 1991-2020 рр. Річні суми сумарної радіації загалом є меншими в період 1961-1990 рр. Аналіз тривалості сонячного сьйва показує, що найбільші показники є характерними для Одеси. Криві річного ходу мають схожу структуру для різних періодів для всіх станцій з максимумами в червні-липні, мінімумами в грудні. Отримані результати дослідження радіаційного режиму дають можливість стверджувати, що енергетичний потенціал України є перспективним для забезпечення паливно-енергетичного комплексу і подальшого розвитку галузі сонячної енергетики країни.

**Ключові слова:** сумарна сонячна радіація, тривалість сонячного сьйва, геліоенергетичні ресурси, альтернативна енергетика, річні показники, багаторічний розподіл, кліматичні норми, потоки сонячної радіації за умов ясного неба, потоки сонячної радіації за середніх умов хмарності.

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