Ministry of Education and Science of Ukraine
Oles Gonchar Dnipro National University

PROVIDING ENERGY-SAVING TECHNOLOGIES: TECHNICAL, ECOLOGICAL AND ECONOMIC ASPECTS

Collective monograph

2019

UDC 620.92:338.45:697.059.7

Is published in accordance with the decision of the Academic Council of the Oles Gonchar Dnipro National University (24.10.2019, protocol № 6)

Reviewers:
M. M. Dron’ - Doctor of Technical Sciences, Professor of the Oles Honchar Dnipro National University;
O. I. Nesterenko - Doctor of Physical and Mathematical Sciences, Professor, Head of the Department of Physics of the State Higher Educational Institution “Ukrainian State University of Chemical Technology”
O. M. Vinichenko - Doctor of Economics, Associate Professor, Professor of the Department of Economics of Industry and Organization of Production of the State Higher Education Institution “Ukrainian State University of Chemical Technology”

Providing energy-saving technologies: technical, ecological and economic aspects. Collective monograph/ under the general edition of dr. of techn. sciences, senior scientific resercher. L.V. Nakashydze Dnipro, DNU, ТОВ „АКЦЕНТ ПП”, 2019. – 134 c.

ISBN

The monograph deals comprehensively with the use of renewable energy sources in terms of the introduction of energy-saving technologies, the solution of problems of increasing the reliability of their use, the formation of a system for assessing the development of renewable energy sources in the face of global challenges, etc. These issues are considered in detail in the analysis of the prospects for the use of elements of protection against electrical overload in solar cells, the results of experimental studies of the implementation of such components. The application of heat pump technologies and energy-active converters of solar radiation energy in the field of resource saving is considered. Materials for solving the problems of acoustic impact on the environment in the implementation of energy-saving technologies, etc. are presented in various ways. This monograph is of scientific and practical importance and is intended for masters, postgraduate students of technical and economic specialties, teachers, researchers and managers engaged in energy saving technologies at industrial enterprises and in the housing and communal sector of Ukraine.

UDC 620.92:338.45:697.059.7

CONTENT

Part 10

QUANTITATIVE AND QUALITATIVE ASPECTS OF SOLAR ENERGY INPUT TO THE WORKING SURFACE OF A SOLAR PHOTOVOLTAIC INSTALLATION DURING GROUND TESTING

L .V. Nakashydze, I. S. Nakashydze

10.1 Features of the conversion of solar radiation upon receipt of the Earth's surface

The distribution of solar energy entering the upper boundary of the Earth’s atmosphere depends on astronomical factors - the luminosity of the Sun, the position of the Earth’s orbit in the Solar system and the characteristics of the Earth’s orbital motion, the inclination of its axis to the plane of the orbit.

A change in the eccentricity of the Earth’s orbit leads to a change in the distance between the Earth and the Sun, and, consequently, the amount of energy supplied per unit time to a unit area perpendicular to the sun's rays at the upper boundary of the atmosphere.

The amount of radiant energy of the Sun coming to the upper boundary of the atmosphere is usually characterized by the solar constant. By the solar constant, we understand the flow of solar radiation at the upper boundary of the atmosphere through an area perpendicular to the sun's rays, with the average distance of the Earth from the Sun. The International Commission on Radiation recommended as the standard value for the solar constant I_0=1,37 kW/m^2. This value corresponds to the total power of solar radiation, called the luminosity of the Sun equal to $3,9 \cdot 10^{23}$ kW [1]

When passing through the atmosphere, the attenuation of radiant energy in the atmosphere is generated by three processes: molecular absorption, molecular scattering, scattering by foreign particles [2].

Absorption of radiant energy in a medium is called attenuation of the radiation flux due to conversion to other types of energy. The scattering of radiant energy in a medium is the transformation of a radiation stream propagating in a medium of a certain direction into flows of various directions. Absorption and scattering are partial or complete.

Molecular absorption of radiation in the atmosphere is the absorption of radiant energy by molecules of optically active atmospheric substances, and molecular scattering is the scattering of radiant energy by individual molecules and variously compacted inhomogeneities of atmospheric gas molecule groups.

The scattering of radiation by foreign particles of the atmosphere is the scattering of radiant energy by solid or liquid particles in the air, which make up haze, clouds, fog, rain, snow, hail, haze.

That is, the physical processes leading to the weakening of solar energy in the atmosphere are due to the presence of thermodynamically active impurities and scattering.

The short-wave radiation of the Sun covers the spectral range from 0,1 μm to 4 μm. The ultraviolet part of the spectrum (0,1...0,39 μm) accounts for 8 %, the visible part of the spectrum (0,39...0,76 μm) – 56 %, the near infrared (0,76...4 μm) - 36 % of the total energy of solar radiation. In real conditions, infrared radiation near the earth is more due to the influence of water vapour.

Solar radiation reaching the Earth’s surface abruptly breaks off at a wavelength of about 0,3 μm. The reason for this is that solar radiation with a wavelength of $\lambda < 0{,}36$ μm is almost completely absorbed by ozone. In addition, ozone has absorption bands in the visible part of the spectrum of 0,44...1,18 μm (Chappuis bands). Especially strong is the absorption in the range of 0,22...0,29 μm (Hartley bands) and in the range of 0,31...0,36 μm (Heggins bands). Ultraviolet radiation is also absorbed by oxygen in the band 0,13...0,24 μm.

Water vapour and carbon dioxide have absorption bands that are mainly in the near infrared area. Water vapour and carbon dioxide absorb solar radiation in an amount of approximately 3,8 % of the solar constant. Part of the solar radiation in the near infrared area absorbs atmospheric aerosol.

The scattering of short-wave radiation in the atmosphere occurs on microinhomogeneities of air, on aerosol particles and cloud particles [3].

The atmospheric effect on the intensity of solar radiation reaching the earth's surface is determined by the “atmospheric mass” (AM). The magnitude of the latter is equal to the secant of the angle between the Sun and the zenith [4].

Fig. 10.1 shows curves illustrating the spectral distribution of the intensity of solar radiation [5].

The upper curve corresponds to the solar spectrum outside the Earth’s atmosphere, i.e. at zero air mass (AM 0). This distribution can be approximated by the distribution of the intensity of the black body at a temperature of 5800 K.

Spectrum AM 0 determines the operation of solar panels on satellites and spacecraft. Spectrum AM 1 corresponds to the distribution of the intensity of solar radiation on the Earth's surface when the Sun is at its zenith; while the total radiation power is 925 W/m^2. Spectrum AM 2 is realized at an angle $\theta = 60^0$. In this case, the total radiation power is 691 W/m^2.

The average radiation intensity on Earth approximately coincides with the intensity of radiation transmitted through the air mass equal to AM 1.5, which corresponds to the position of the Sun at an angle of 45^0 to the horizon. Fig. 10.2 shows the distribution of the number of photons per unit energy interval per 1 cm^2 for 1 s under conditions of AM 0 and AM 1.5 [6]. The total power of solar radiation at AM 1.5 is 844 W/m^2.

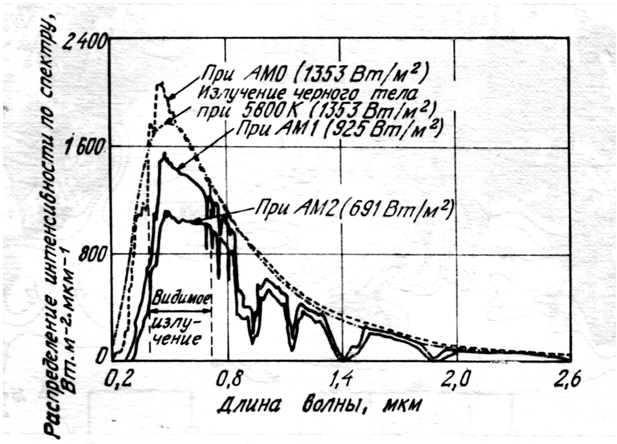


Fig. 10.1 - The spectral distribution of the intensity of solar radiation

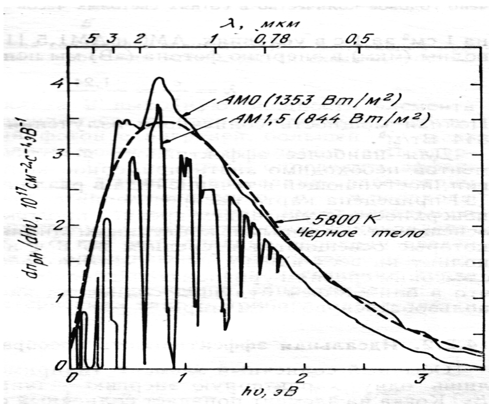


Fig. 10.2 - The distribution of the number of photons at different values of the atmospheric mass

The short-wave radiation of the Sun, passing through the Earth’s atmosphere, is partially absorbed by thermodynamically active impurities, partially scattered and enters the underlying surface in the form of total radiation. The atmosphere acts as a kind of filter that determines how much radiant energy enters the underlying surface. The atmosphere also emits long-wave radiation in the direction of the underlying surface.

The total radiation (S) arriving at the underlying surface is not completely absorbed. Part of it is reflected. The albedo characterizes the fraction of the reflected part of the total radiation of the Sun (α). Its value is influenced by the nature of the terrain, the type and condition of the vegetation cover, the presence of snow, etc. In the summer months, the albedo of the earth is quite stable, and its value ranges from 0,16...0,28. In the winter months, with bare ground, the albedo is 0,07...0,1, and with snow cover it can reach 0,89. For spacecraft, located at a high altitude, the albedo of different surfaces and can be averaged using an average planetary value equal to 0,39 [7].

Cloudiness has a great effect on the attenuation of solar radiation, on the ratio between the direct and scattered components. If under the influence of a cloudless atmosphere the flow of solar radiation is weakened by an average of 20 %, then cloudiness weakens solar radiation by another 20...30%. Thus, the earth's surface reaches an average of 50...60 % of solar radiation entering the upper boundary of the atmosphere. The dependence of the total radiation on the amount of cloudiness can be represented as

$$S = S_0[1(a+bn)n], \tag{10.1}$$

where S_0 - total radiation flux in the absence of cloudiness; n - number of clouds in fractions of a unit; a, b - regression coefficients depending on latitude.

The formula shows that if 80 % of the insolation doesn’t fall on the earth in a cloudless sky, then at n = 0,5 its share decreases to 65 %, and at n = 1 to 20 %.

The main climate indicators for cloud numbers are: average value, repeatability of various cloudiness marks and average number of clear and cloudy days.

There are several approaches to calculating the arrival of solar radiation on a solar cell. According to one of them, built on the basis of the principle of Liu and Jordon, the equation for calculating the intensity of the incident solar radiation flux taking into account the angular sensitivity of solar cells has the form:

$$S = (P_S I_S + P_D I_D)\, S(\alpha), \tag{10.2}$$

where I_S - is the flux density of direct solar radiation incident on a horizontal surface, W/m^2; I_D - flux density of scattered solar radiation incident on a horizontal surface, W/m^2; P_S, P_D - solar cells’s position coefficients for direct and solar scattered radiation, respectively; $S(\alpha)$ - angular sensitivity of the solar cell.

The coefficients of the position of the solar cells are determined by the formulas:

$$P_D = cos^2 \frac{\beta}{2}$$

$$P_S = \frac{cos\,\gamma}{sinh_{\Theta}} \tag{10.3}$$

where β - angle of inclination of the solar cell to the horizon; cos γ - the total angle of incidence of sunlight on the surface of the solar cell; h_θ - angle of the height of the sun above the horizon.

The integral fluxes of direct and scattered radiation depend on the optical mass of the atmosphere (τ), as well as on the angular height of the Sun (h_θ). This dependence has the form [3]

$$S = \frac{I_0 \sinh_{\Theta}}{1 + 2\varepsilon\tau \cos ech_{\Theta}}, \tag{10.4}$$

where ε - some factor depending on the angular height of the sun.

The greatest angular height of the Sun at local noon and the optical mass of the atmosphere depend on the latitude of the place.

Thus, it is obvious that among the large list of criteria characterizing the solar radiation entering the SPVU surface, the most definite are the data on the power and spectral composition of solar radiation behind the atmosphere.

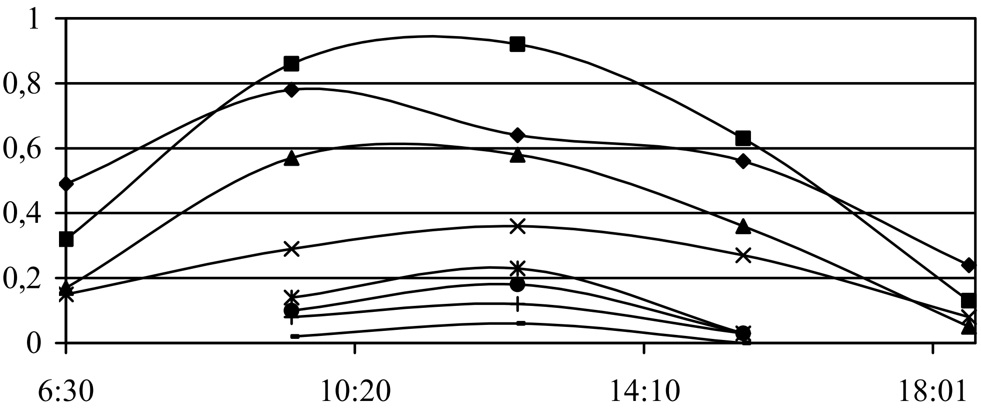
The experimental measurements necessary to determine the dependence of the changes in the energy-generating ability of solar cells used in the composition of SPVU on the level of solar illumination were carried out under conditions of ground-based natural insolation. However, they can be approximated, taking into account the above assumptions, for recalculation for conditions without the presence of the atmosphere.

Experimental measurements were carried out in Dnipro-city, therefore meteorological data were analysed to determine the nature and intensity of solar radiation in the Dnipro region.

10.2 Solar radiation and the regime of sunshine in the Dnipro region

According to [8], the annual possible arrival of direct solar radiation with a clear sky on a horizontal surface in the Dnipro region is $1,30 \cdot 10^3$kW·h/m^2. In the case of average cloud cover, these values decrease to $0,80 \cdot 10^3$kW·h m^2. The annual arrival of diffuse radiant energy in a clear sky - 0,40-0,47 $\cdot 10^3$kW·h/m^2.

In [9], the results of statistical processing of actinometer measurements of the regime of sunshine in the Dnieper region are presented, they are presented by graphs (Fig. 10.3, Fig. 10.4). The authors showed that the share of direct radiation in the total varies over the course of the year. So, in the period from November to February, the contribution of direct radiation is 30%, and from March to October - 40...65%. In the annual course, the maximum monthly amounts of total and direct radiation to the horizontal surface is observed in June-July, when the total radiation reaches 0,20 - 0,24 $\cdot 10^3$kW/m^2, straight - 0,17 - 0,19 $\cdot 10^3$kW/m^2, straight on a horizontal surface - 0,11 - 0,13 $\cdot 10^3$kW/m^2.



—◆— direct solar radiation incident on a perpendicular surface - July

—■— total radiation intensity - July

—▲— direct solar radiation incident on a horizontal surface - July

—×— scattered radiation intensity – July

—✳— direct solar radiation incident on a perpendicular surface - December

—●— total radiation intensity - December

—+— scattered radiation intensity - December

—-— direct solar radiation incident on a horizontal surface - December

Fig. 10.3 - The intensity of solar radiation. Daily move

The sharp increase in the monthly amounts of direct and total radiation from February to March is explained by a decrease in cloudiness, an increase in the height of the Sun and an increase in the duration of daylight hours.

The albedo of natural surfaces in the Dnipro region varies, in the summer within 14...24 %. In the period with unstable snow cover characteristic of the region, the average fluctuates from 19,5 to 48%. The maximum albedo is observed in the period of the third decade of December - the first half of February.

In absolute terms, the annual radiation balance is about $0{,}63 \cdot 10^3$ kW/m^2. The period with a positive radiation balance is more than 10 months. The change in the balance sign occurs in early December and late January.

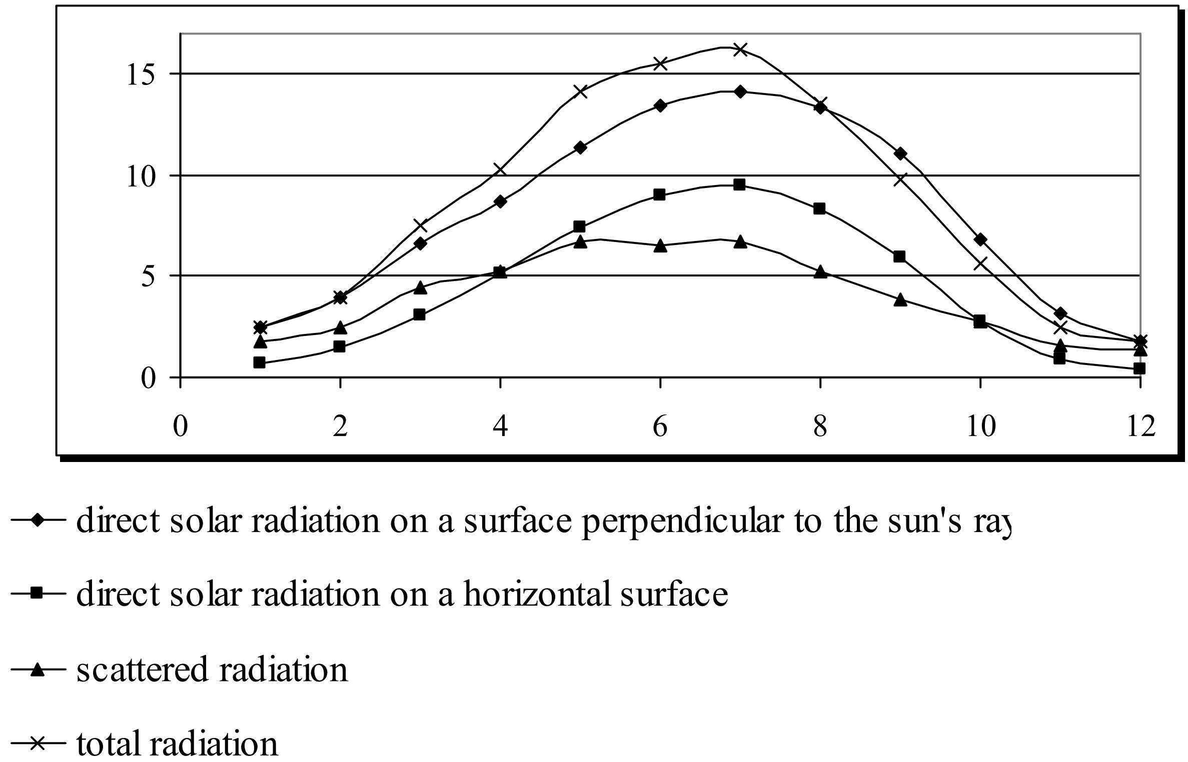


Fig. 10.4 - Monthly average amounts of radiation. Annual move

The sunniest months are May-August, the least sunny days in November-February. In July, the number of hours of sunshine can reach 348 or more. In December, the duration of sunshine is minimal and is 35...40 hours. About 70 % of possible radiation falls in July, 10...20 % in December.

Atmospheric pollution in large cities leads to a significant decrease in the intensity of direct solar radiation and reduces the number of hours of sunshine.

10.3 Influence of ground test features on the actual characteristics of a solar photovoltaic installation

The main features of the climate of Ukraine are formed under the influence of a number of factors: solar radiation, atmospheric circulation, elevation, etc. In [10], data on solar radiation for the territory of Ukraine are presented, and zoning is carried out according to the amount of incoming solar radiation.

Ukraine in its geographical position occupies a relatively small territory (about 7^0). Therefore, the change in the maximum value of the intensity of solar radiation throughout Ukraine can be described by a linear relationship:

$$E_m = E_{mB}[1+0,024(\varphi_B - \varphi_{reg})], \qquad (10.5)$$

E_{mB} - the maximum value of the intensity of solar radiation at the base observation point, W/m^2; φ_B, φ_{reg} - latitude of the base and region, degrees

If for the base, take the intensity of solar radiation in Kyiv (there are reference data for it), then φ_B will be equal to 50.5^0 bp. w.

Equation (10.5) can be used to determine the intensity of solar radiation in the design of solar photovoltaic installations.

The territory of Ukraine can be divided into regions with similar features of the spatio-temporal structures of solar radiation fields [11].

Chernihiv region, Sumy region, Zhytomyr region, Rivne region, Lutsk region, Ternopil region, Lviv region, Ivano-Frankivsk region, Chernivtsi region, northern part of Khmelnytsky region, northern part of Kyiv region have a total annual solar radiation of up to $1,164 \cdot 10^3$ kW·h/m^2.

Uzhgorod region is especially interesting. The western part of this region refers to areas where the total radiation reaches $1,280 \cdot 10^3$ kW·h/m^2. The central part of Uzhgorod region has a total solar radiation level of up to $1,219 \cdot 10^3$ kW·h/m^2. In the eastern part of this region, the level of total solar radiation reaches $1,164 \cdot 10^3$ kW·h/m^2.

The south of the Khmelnytsky region, Vinnytsia region, the central part and the southern part of the Kyiv region, Cherkasy region, Poltava region, the northern part of the Kharkiv region have a total annual solar radiation of up to $1,219 \cdot 10^3$ kW·h/m^2.

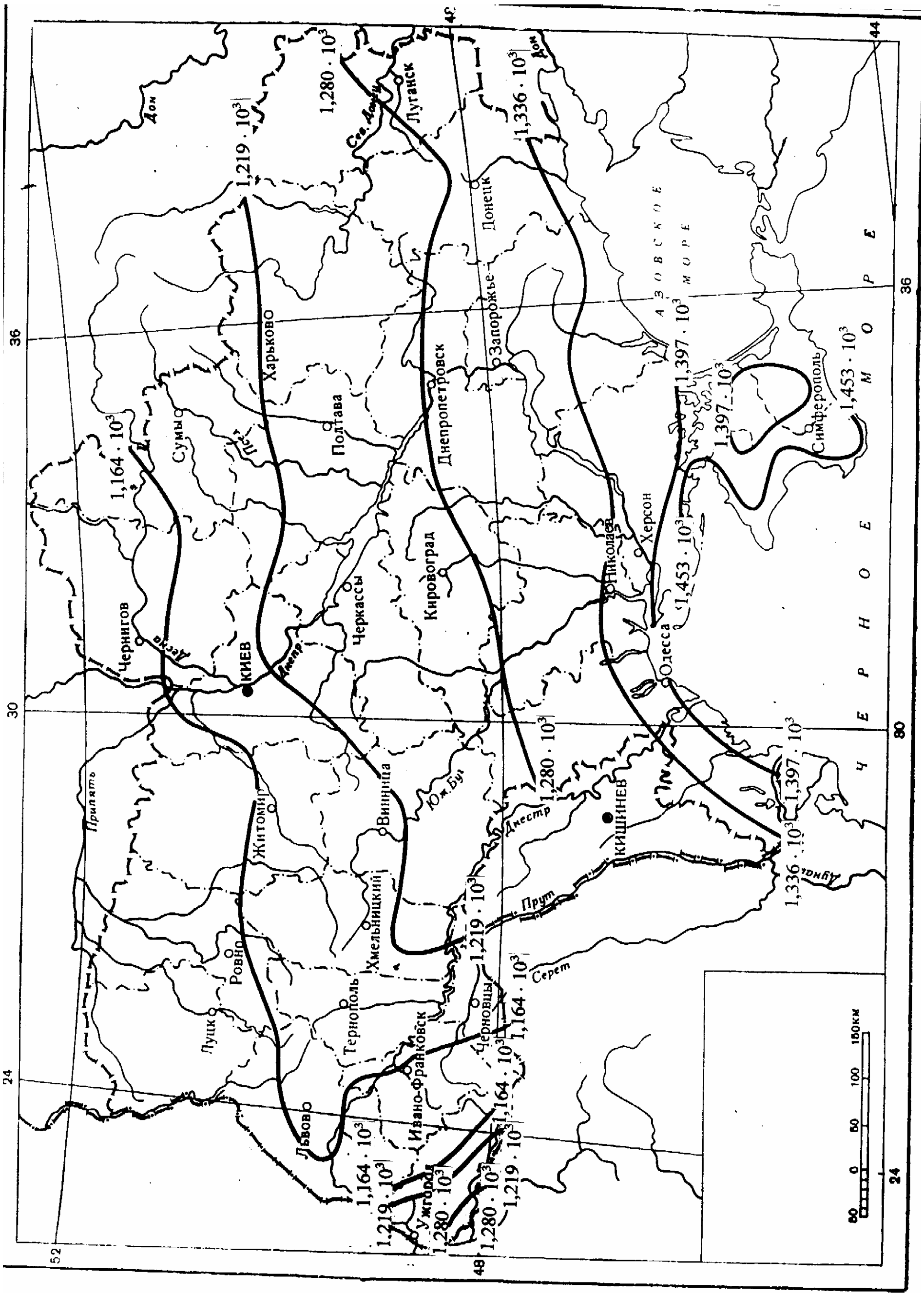


Fig. 10.5 - The total annual solar radiation (kW · h/m^2)

Northern part of Odessa region, Kirovograd region, Dnipropetrovsk region, northern part of Zaporizhzhya region, northern and central part of Donetsk region, Lugansk region, northern part of Mykolaiv region have a total annual solar radiation of up to 1,280 · 10^3 kW·h/m^2.

On the territory of the central part of Odessa region, the southern part of Mykolaiv region, Zaporizhzhya region, southern part of Donetsk region total solar radiation arrives up to 1,336·10^3 kW·h/m^2.

In the southern part of Odessa region, Kherson region, the central and eastern parts of Crimea, the total annual solar radiation reaches $1{,}397{\cdot}10^3$ kW·h/m^2.

In the territory of the western and southern parts of Crimea, the total and annual solar radiation reaches $1{,}453{\cdot}10^3$ kW·h/m^2.

The main purpose of the climatic isoline map is that with its help it is possible to obtain data by interpolation at points where there are no meteorological observations. The climate map also gives a visual representation of the basic laws of climate.

An analysis of the data showed that in cloudless weather, the amount of energy that enters the northern regions of Ukraine is only 16 % less than in the southern. However, the true value of the incoming energy substantially depends on many factors, primarily on cloudiness and the state of the atmosphere. If the monthly energy supply is calculated taking into account the coefficient of sunshine, then the total energy value for the year in the northern regions will decrease by almost 2 times, and in the southern only 1,56 times. Thus, it turns out that the amount of energy that enters the southern territories of Ukraine (1270 kW·h/m^2) is 1,51 times more than in the northern regions of Ukraine (840 kW·h/m^2) [11].

The amount of solar energy entering the surface of a solar photovoltaic installation in the Dnipro region, throughout Ukraine, is different, but these differences are not as dramatic as might be expected. Thus, the research results obtained in the course of this work can be used not only in the Dnipro region.

10.3 Conclusions

An analysis of literary sources (data) showed that information on the power and spectral composition of solar radiation is most accurate for conditions outside the earth's atmosphere. Using for space-based SPVU in the design and construction work the data obtained during experimental measurements under conditions of natural ground insolation, when determining the dependence of the change in the energy-generating ability of solar cells on the level of solar illumination, is possible:

- subject to assumptions, i.e. approximation of data to conditions without the presence of atmosphere.

- after considering the overall dynamics of the change in the measured values, i.e. excluding absolute values.

The quantitative and qualitative composition of solar energy supplied during the year to an experimental solar photovoltaic installation located in the Dnipro region is considered.

To solve the problem of the widespread use in ground energy of the data obtained during the experimental work, based on a comparative analysis of meteorological observations, zoning of the territory of Ukraine was carried out depending on the annual amount of solar energy supplied to the surface. It is noted that the amount of energy that enters the southern territories of Ukraine (1270 kW·h/m^2) is 1,51 times more than in the northern regions of Ukraine (840 kW·h/m^2). It is concluded that it is possible to use the results obtained in this work not only in the Dnipro region, but also more widely.

References

1. Makarova E.A., Haritonov A.V., Kazachevskaya T.V. Potok solnechnogo izlucheniya.- M.: Nauka. 1991.-400s.

2. Lazarev L.P. Optiko-elektronnyie priboryi navedeniya. - M.: Mashinostroenie, 1989.- 516s.

3. Klimatologiya, pod red. Drozdova O.A., prof. Kobyisheva N.V., Gidrometeoizdat, Leningrad, 1989

4. Fizika poluprovodnikovyih priborov. -M.:Mir, 1984, -Kn.2. 456s.

5. Thekaekara M. P. Data on Incident Solar Energy, Suppl. Proc.20th Ann.Meet.Inst.Environ. Sci., 1974, p.21

6. Henry C. H. Limiting Efficiency of Ideal Single and Multiple Energy Gap Terrestrial Solar Cells, J. Appl. Phys., 51, 4494 (1980)

7. Kondratev K.Ya. Aktinometriya. Gidrometizdat, 1965

8. Spravochnik po klimatu SSSR. L. 1966. vyip. 10, ch.1, ch.3, ch.6

9. Kurochkin G.F., Vorobev G.M. Fizicheskie printsipyi snizheniya materialoemkosti preobrazovateley vozobnovlyaemoy energii: ucheb. posobie. Dnepropetrovsk: DGU, 1989.144s.

10. Klimaticheskiy atlas Ukrainskoy SSSR. – L.: Gidrometeoizdat, 1968. 238 s.

11. Kukushkin V.I., Levenko A.S. Malaya energetika. Analiz sostoyaniya i perspektivyi razvitiya.- D.: ART-PRESS, 2005.-100s.

Scientific edition

L. V. Nakashydze, A. S. Tonkoshkur, A. V. Ivanchenko, S. V. Mazurik, V. O. Gabrinets, I .V. Tytarenko, G. L. Gnatiuk, A. V. Trofimenko, G. I. Sokol, V. Yu. Kotlov, T. L. Savchuk, S. Ju. Kyrychenko,T. V. Hilorme, O. K. Yelisyeyeva, I S. Nakashydze

PROVIDING ENERGY-SAVING TECHNOLOGIES: TECHNICAL, ECOLOGICAL AND ECONOMIC ASPECTS

Collective monograph
(in English)

Proofreader of English: Nakashydze I. S.

Submitted to the publisher 12.12.2019. Signed for print 13.12.2019.
Format 60x84/16. Offset paper. Academy headset. Offset printing. Умовн. Print.pages 6,92. Circulation 300 copies. Order № 404.
Issued and printed в ТОВ „Акцент ПП."
вул. Ларіонова, 145, м. Дніпропетровськ, 49052
Тел (056) 794-61-04 (05)
Certificate of the subject of publishing
Серія ДК №4766 від 04.09.2014