УДК 502.62
AGRIS P05
https://doi.org/10.33619/2414-2948/70/06

SOLAR ENERGY RESOURCES OF NAKHCHIVAN

*©**Novruzova S.,** ORCID: 0000-0003-4230-0661, Nakhchivan State University, Nakhchivan, Azerbaijan, sevincrzayeva1969@gmail.com*

РЕСУРСЫ СОЛНЕЧНОЙ ЭНЕРГИИ НАХИЧЕВАНИ

*©**Новрузова С. Ю.,** ORCID: 0000-0003-4230-0661, Нахичеванский государственный университет, г. Нахичевань, Азербайджан, sevincrzayeva1969@gmail.com*

Abstract. The presented article examines the issues of energy security of the Nakhchivan Autonomous Republic, which is an integral part of the Republic of Azerbaijan, and the use of renewable energy in its provision. For this purpose, the solar energy resources of the Autonomous Republic were studied. The study used theoretical, computational, observational and comparative analysis methods to estimate solar energy as a renewable energy resource. The main source for assessing the potential of solar energy of the Autonomous Republic — experimental and observation materials of the USSR Hydrometeorological Committee on the Republic of Azerbaijan and NAR for 1960–1980, the results of researches of the Institute of Geography of the Azerbaijan National Academy of Sciences for 1936–1950, Nakhchivan AR experimental-observation materials of the Hydrometeorological Center for 1995–2015, static indicators of Nakhchivan Solar Power Plant for 2016–2017, as well as the results of theoretical and computational research were used. As a result of the study, it was determined that the annual value of total radiation (Q) in the horizontal area was 7541 and 6204 MC/m^2, respectively, in the clear and medium cloudy sky. At the same time, the average annual transparency coefficient was 0.8229, 0.811 in winter and 0.897 in summer. The annual value of total radiation (Q) of the horizontal field in the territory of the NAR is higher than in other regions of the country, and the coefficient of transparency of the atmosphere is higher than in other regions, too. At the same time, the duration of solar radiation in the NAR is high and is 2792 hours. Formulas have been proposed to calculate the value of solar radiation falling on a horizontal surface on the basis of many years of experimental and observational materials. Using these calculation formulas, it is possible to calculate the total solar radiation on the horizontal surface for any area of the NAR.

Аннотация. В представленной статье рассматриваются вопросы энергетической безопасности Нахичеванской Автономной Республики. Для этого были изучены ресурсы солнечной энергии республики. В исследовании использовались теоретические, вычислительные, наблюдательные и сравнительные методы анализа для оценки солнечной энергии как возобновляемого источника энергии. Основной источник оценки потенциала солнечной энергии Автономной Республики — экспериментальные и наблюдательные материалы Гидрометеорологического комитета СССР по Азербайджанской Республике и НАР за 1960–1980 годы, результаты исследований Института географии Национальной академии Азербайджана за 1936–1950 гг., Нахичеванской АР, материалы экспериментальных наблюдений Гидрометцентра за 1995–2015 гг., статические показатели Нахичеванской солнечной электростанции за 2016–2017 гг., а также результаты теоретических и расчетных исследований. В результате исследования было определено, что годовое значение суммарной радиации (Q) в горизонтальной области составило 7541 и 6204 МС/м^2 соответственно при ясном и среднем небе. При этом среднегодовой коэффициент прозрачности составил 0,8229, 0,811 зимой и 0,897 летом. Годовое значение суммарной радиации (Q) горизонтального поля на территории НАР выше, чем в других регионах страны, и коэффициент прозрачности атмосферы также выше, чем в других регионах. В то же время продолжительность солнечной радиации в НАР высока и составляет 2792 часа. На основе многолетних экспериментальных и наблюдательных материалов предложены формулы для расчета величины солнечного излучения, падающего на горизонтальную поверхность. Используя эти расчетные формулы, можно рассчитать общую солнечную радиацию на горизонтальной поверхности для любого района НАР.

Keywords: energy security, renewable energy, solar energy, green tariff.

Ключевые слова: энергетическая безопасность, возобновляемые источники энергии, солнечная энергия, зеленый тариф.

Introduction

Solar energy is one of the main types of renewable energy. The use of this energy has always been relevant in human history, especially since the XVII century. Starting from the 70s of the XX century, new technological devices for the use of solar energy were created in the world for the production of electricity and heat. The end of the XX century - the beginning of the XXI century saw a serious leap in this area. Thus, in 1985, the installed capacity for electricity generation in the world was 2.1 MW, while in 2004 it was 4.4x103 MW. In other words, there was an increase of about 200 times. The installed capacity was 102 GW in 2012, 228 GW in 2015 and 306 GW in 2016. In this area, China (46%), the United States (20%), Japan (11.5%) and others are leaders [5–6].

The problem of energy security is relevant for many countries around the world, including the Nakhchivan Autonomous Republic. The use of renewable energy in Nakhchivan is very relevant in terms of both energy security and the requirements of the following two international conventions [1-7].

- United Nations Framework Convention on Climate Change (UNFCCC), adopted in Rio de Janeiro in 1992 (09.05.1992) with the participation of representatives from 161 countries;
- "Kyoto Protocol" signed in December 1997 in Kyoto, Japan.

The Milli Majlis of the Republic of Azerbaijan ratified the FCCC in 1995 and the Kyoto Protocol in 2000.

The use of renewable energy is an urgent problem in Azerbaijan, and one of the main tasks in carrying out construction work in the liberated regions of Azerbaijan in 2020 was the use of renewable energy.

According to static data at the end of 2020, the installed capacity of renewable energy in the electric power system of the Autonomous Republic is about 38.7% (total generation capacity — 239,900 kW, renewable energy generation capacity — 92,900 kW).

Problem statement

One of the main problems in the use of solar energy is its cost and profitability of solar power plants (SPPs). From this point of view, the application of the "Green Tariff" policy is relevant [2-5, 7].

According to experts of the International Energy Agency (IEA), in the next 40-50 years, the annual production of solar power plants (SPPs) in the application of new innovative technologies will be 9,000 TeraWt, which will account for 20-25% of total electricity generation. This increase can be explained by several factors:

- first of all, the declining production of fossil fuels and rising prices;
- reduction of the cost and payback period of electricity at SPPs as a result of the application of new innovative technologies (according to the US Department of Energy, the cost of electricity will not exceed 4 cents by 2020-2025);
- with increasing requirements for social efficiency (environmental safety requirements).

In this work, theoretical-calculation, observation and comparative analysis methods were used in the assessment of solar energy resource as a renewable energy resource of NAR.

The following main sources were used to assess the solar energy potential of the NAR:

- Experimental-observation materials of the USSR Hydrometeorological Committee on the Republic of Azerbaijan and NAR for 1960-1980;
- The results of research of the Institute of Geography of the National Academy of Sciences of Azerbaijan for 1936-1950;
- Experimental-observation materials of the Hydrometeorological center of Nakhchivan AR for 1995-2015;
- Data of Nakhchivan Solar Power Plant for 2016-2017.

The results of the study

The results of the study. Photoelectric and heliothermic methods are considered to be more promising for electricity generation. Therefore, we will pay special attention to the problem of electricity generation by these methods.

The average hourly electricity generation in a photovoltaic HPP can be determined by the following formula [8, 9].

$$Nel = Q \cdot \eta \quad (1)$$

Here: Q– is the total radiation falling on the horizontal surface, KW/m^2. η– is the efficiency of the concentrate.

The total solar radiation falling on the horizontal surface can be calculated as follows [10]:

$$Q = S + D + R \quad (2)$$

Here: S — is direct sunlight falling on the surface, KW/m^2. D — is the scattering of solar radiation on the surface, KW/m^2. R — is the radiation reflected from the earth's surface, KW/m^2.

The amount of sunlight falling on the surface can be calculated by the following formula.

$$S = S_{ort} \cdot \cos\theta \quad (3)$$

Here: S_{ort} — is direct sunlight to the surface with orthogonal radiation, KW/m^2. θ — is the angle of incidence of direct sunlight on the surface, rad.

$$S_{ort} = S_0 \cdot \sin\alpha/(\sin\alpha+C) \quad (4)$$

Here: S0 is the solar radiation at the upper boundary of the Earth's atmosphere, KW/m^2. α — is the height of the sun, rad. C — is a quantity that characterizes the transparency of the atmosphere.

$$S_0 = S^*_0\,[1+0{,}033\cos(360/365 \cdot d)] \quad (5)$$

Here: S^*_0 — is solar constant, $S^*_0 = 1380\ W/m^2$. d — is the consecutive number of the day of the year starting from January 1.

The height of the day can be calculated by the following formula.

$$\mathrm{Sin}\alpha = \sin\varphi \cdot \sin\delta + \cos\delta \cdot \cos\varphi \cdot \cos\omega \quad (6)$$

Here: φ — is the width of the area, rad. δ — is the angle of inclination of the sun, rad. ω — is the hour angle of the sun, rad.

The angle of inclination of the sun can be calculated as follows:

$$\delta = \delta_0 \cdot \sin(360 \cdot (284 + d)/365) \quad (7)$$

Here: δ0 = 23.45 is the maximum slope. 284 is the number of days from March 21 to December 31.

The hour angle of the sun can be calculated as follows:

$$\omega = 15 \cdot (t - t') + E(t) + (\varphi - \varphi_{zona}) \quad (8)$$

Here: t — is the moment of time under consideration, an hour. t ′ — local time, hour in the solar half-day in the time zone under consideration. E (t) — is the time equation. φ — is the geographical length of a given area, rad. φ_{zona} — is the geographical length of the meridian plane that coincides with the true midday sun, rad.

$$E(t) = 7{,}53\cos(B) + 1{,}5\sin(B) - 9{,}87\sin(2B) \quad (9)$$

$$B = 360 \cdot (d - 81)/365 \quad (10)$$

Here: the number 81 is the number of days from December 31 to March 21.

The angle of incidence of direct sunlight on the surface can be determined by the following formula:

$$\mathrm{Cos}\theta = \sin\delta \cdot \cos\varphi \cdot \cos\beta - \sin\delta \cdot \cos\varphi \cdot \sin\beta \cdot \cos\gamma + \cos\delta \cdot \cos\varphi \cdot \cos\omega + \cos\delta \cdot \sin\varphi \cdot \sin\beta \cdot \cos\gamma \cdot \cos\omega + \cos\delta \cdot \sin\beta \cdot \sin\gamma \cdot \sin\omega \quad (11)$$

Isotropic or anisotropic models can be used to calculate the scattering of solar radiation on the surface. According to J. Heyan's anisotropic model, this quantity (D) can be calculated. It can also be calculated based on Klasser's model [10].

The value of radiation reflected on the Earth's surface can be calculated as follows:

$$R = Q \cdot A_k/100 \quad (12)$$

Here: Q is the total solar radiation falling on the earth's surface, KW/m^2. A_k — is the albedo of the surface.

The ratio of the rays reflected by the sun's rays to the earth's surface is called albedo and is expressed as a percentage. The Earth's albedo accounts for 26% of the total energy flow from the sun, so $A_k = 0.26$.

Academician A. Hashimov and his colleagues used 6 types of design schemes of photoelectric devices in the calculation of energy production of photovoltaic devices and applied another method [8]. His reports show that the annual specific electricity generation in the Nakhchivan Autonomous

Republic is higher than in other regions of the country in all constructive types of photovoltaic devices. At the same time, the third module of the photovoltaic device (photovoltaic module rotating parallel to the Earth's axis) has a higher annual specific power generation.

M.Kazimov, an employee of the "Institute of Natural Resources" of the Nakhchivan branch of the National Academy of Sciences of Azerbaijan, used an empirical equation to calculate the value of the daily intensity of sunlight in his research work. In his reports, the value of the daily intensity of sunlight on the earth's surface (Ii) was 975 W/m^2 [11].

$I_i = \dot{I}_0 \cdot 0{,}7^{(AM \cdot 678)} = 1367 \cdot 0{,}721 = 975$ W/m^2

Here: I_i — is the intensity in the area perpendicular to the sun's rays, W/m^2. AM is the mass of the atmosphere. 0.7 — indicates that 70% of the sun's rays reaching the atmosphere reach the earth's surface. 0.678 is a factor that takes into account the diversity of the atmosphere.

M. Kazimov used a simpler method to calculate the density of solar radiation falling on the horizontal surface.

$$S = S' \cdot \sin h \qquad (13)$$

Here: S ′— is the solar constant.тh is the angle of incidence of the sun's rays on the earth's surface.

In the Nakhchivan Autonomous Republic Hmax = 74.5° on sunny summer days and Hmin = 27.5° on sunny winter days. At the same time, in M. Kazimov's calculations, the transparency coefficient of the atmosphere was taken as 0.9 and 0.8 in summer and winter, respectively. In this case, the total energy of solar radiation coming to the territory of the Autonomous Republic is S = 1214 Bt/m^2 on hot summer days and S = 567 Bt/m^2 in winter.

It should be noted that the multi-year experimental and observation materials of the NAR are 10-30% less than the results obtained from M. Kazimov's calculations. Thus, experimental data show that the total energy of the sun's rays is S = 900 Bt/m^2 on hot summer days and S = 550 Bt/m^2 in winter.

In our calculations, we used long-term (1960-1980 and 2004-2015) experimental-observation materials of Nakhchivan Hydrometeorological Station [12-14].

Table 1 shows the values of total radiation (Q) and experimental observations on the horizontal surface for NMR. As can be seen from the table, the maximum value of Q is observed in clear sky in June (917 MC/m^2), in medium cloudy sky in July (850 MC/m^2) and its minimum value is observed in both cases in December (299 and 193 MC/m^2). At this time, the transparency coefficient of the atmosphere was 0.93 and 0.646, respectively.

Table 1

ESTIMATES OF EXPERIMENTAL OBSERVATIONS
OF TOTAL RADIATION IN THE HORIZONTAL SURFACE FOR NMR

Months of the year	*In the clear sky, MC/m^2*		*In the medium cloudy sky, MC/m^2*	
	daily	*monthly*	*daily*	*monthly*
1	10,98	340	7,13	221
2	14,50	409	10,61	297
3	21,28	660	14,72	456
4	26,12	784	18,82	565
5	29,22	906	23,02	714
6	30,58	917	27,08	812
7	29,02	890	27,42	850

Months of the year	*In the clear sky, MC/m²*		*In the medium cloudy sky, MC/m²*	
	daily	*monthly*	*daily*	*monthly*
8	26,08	808	24,8	769
9	21,68	650	20,30	609
10	16,74	519	14,17	439
11	11,98	359	9,29	279
12	9,54	299	6,23	193

The annual value of total radiation (Q) to the horizontal surface was 7541 and 6204 MC/m^2, respectively, in clear and medium cloudy skies. At the same time, the average annual transparency coefficient was 0.8229, 0.811 in winter and 0.897 in summer. Table 2 presents a comparison of the annual value of total radiation (Q) to the horizontal surface in the NAR with other regions of the country. As can be seen from Table 2, the annual value of total radiation (Q) to the horizontal surface in the NAR is higher than in other regions of the country, while the transparency coefficient of the atmosphere is higher than in other regions. At the same time, the duration of solar radiation in the NAR is high and is 2792 hours. This once again shows that the use of solar energy in the NAR is more efficient.

Table 2

Comparative analysis of annual value of total radiation (Q) to the horizontal surface in Azerbaijan

Observation zones	*In medium cloudy sky, MC/m²*		*In clear sky, MC/m²*	*Transparency coefficient*
	annual	*albedo*	*annual*	
NAR	6204	0,26	7541	0,822
Baku (Oil Rocks)	4867	0,08	6384	0,762
Baku (Pirallahıi Island)	5679	0,19	7282	0,78
Goygol-Shamkir	5011	0,43	8619	0,58
Mingachevir	5158	0,21	7017	0,735

The power of the photoelectric SPP can be calculated based on the experimental observations of the annual value of total radiation (Q) in the horizontal field (Table 3).

Table 3

ELECTRIC POWER OF A SOLAR POWER PLANT

Observation zones	*In medium cloudy sky, Kwh/m²*		*In the clear sky, Kwh/m²*		*Annual average value, Kwh/m²*
	E.F. = 0,2	*E.F. = 0,3*	*E.F. = 0,2*	*E.F. = 0,3*	*E.F. = 0,2*
NAR	345	517	419	628	382
Baku (Oil Rocks)	270	406	355	532	313
Baku (Pirallahi Island)	316	473	405	607	361
Goygol-Shamkir	278	418	479	718	379
Mingachevir	287	430	390	585	339

In the absence of meteorological or experimental data in the literature, it is proposed to calculate the total solar radiation to the horizontal surface by the following formula [15].

$$Q = Q_{gs} \text{ x } (0.29 \cos\varphi + 0.52n / N) \quad (14)$$

Here: Q_{gs} = 9830 W hours / m2 day – is the sun constant. φ - is the latitude, for NAR φ = 39º is assumed. N — were the possible hours of sunlight. N — were the actual hours of sunlight.

In the Nakhchivan Autonomous Republic N = 2792 hours. Many years of experience show that the average quadratic difference of solar radiation in the Autonomous Republic is 144 days. With the above formula (14) it is possible to write the experimental data of NAR with an error of 11-17%. A comparison of experimental and observation materials with this formula shows that in order to increase the accuracy of the formula and ensure that the error does not exceed 10%, the coefficient of the second addition in parentheses in the formula should be taken as 0.65. In this case, the total solar radiation on the horizontal surface for any area of the NAR can be calculated by formula (15) without actinometric observation.

$$Q = Q_{gs} \text{ x } (0{,}29 \cos\varphi + 0{,}65 \text{ n/N}) \quad (15)$$

The formulas (14) and (15) can also be used to calculate the value of total solar radiation to the horizontal surface in the Igdir Province of the Republic of Turkey.

Analysis of the literature on the heat balance of the Republic of Azerbaijan shows that actinometric observation in the country was organized in the 50s of the twentieth century. There is no generalized regularity for the territory of our country. Thus, the climatic conditions of the NAR differ from other parts of Azerbaijan and are more similar to the climate of Central Asia. Therefore, the total solar radiation on the horizontal surface can be calculated by formula (16) depending on the altitude.

$$Q = 140 + 0.005 \text{ x } h \quad (16)$$

Here: h — indicates the height of the area above sea level, m.

The height of NAR is 800-4000 m above sea level, the average height above sea level is about 1000 meters.

As mentioned above, there was a hydrometeorological center in the NAR in 1960-1980, and actinometric observations were conducted in this center. However, despite the increase in the number of hydrometeorological centers in the NAR in the 90s of the XX century and the beginning of the XXI century, actinometric observation was not carried out in full. Thus, there is no information on the measurement of solar radiation in the experimental journals of the hydrometeorological centers of the NAR. Therefore, we used the indirect method. As an indirect method, we used the equation for the relationship between total solar radiation and air temperature. E. Shikhlinsky proposed the equations of the relationship between total solar radiation (Kcal/cm^2) and air temperature for the South Caucasus and Central Asia as follows [14].

$$Q = 0{,}134t^2 – 5{,}12t + 173{,}5 \quad (17)$$

Here: t is the temperature of the atmosphere in the observed area, °C.

$$Q = 0{,}00000225\theta^2 – 0{,}0119\theta + 140{,}5 \quad (18)$$

$$\theta = 245t – 2009 \quad (19)$$

It is proposed to use the proposed equation (17) when the annual temperature is greater than 10^0C.

Our reports show that when equations (17) and (18) take the average annual temperature, the error between the result obtained and the result of the experiment is large. However, when the average temperature for the summer period is taken instead of the average annual temperature, as well as when the latter number in addition in equations (17) and (18), 193 and 160, respectively, the error is less than 5%. Therefore, the following equations are proposed for the calculation of total solar radiation in the NAR.

$$Q = 0{,}134t^2 - 5{,}12t + 190 \quad (20)$$

$$Q = 0{,}00000225\theta^2 - 0{,}0119\theta + 160 \quad (21)$$

The results of the proposed formulas for the calculations coincide with the performance of Nakhchivan HPP with an error of 5%. This again demonstrates the reliability of the reporting formulas. In order to use solar energy in Nakhchivan AR in 2015-2017, a solar power plant was built on the left side of the Nakhchivan-Shahbuz road and at the 13th and 15th kilometers, with 78,684 solar panels produced by the Belgian company Soltech with a capacity of 22,000 kW, and the total area of 129,000 m2 and 15.5% efficiency factor and connected to the grid in January 2016. Later, the capacity of the SPP was increased by 3,000 KW.

The amount of electricity generated at Nakhchivan SPP in 2016 was 30 million Kwh. In September 2017, the installed capacity of the SPP was increased to 22,000 kW, and then to 25,000 kW. The experience of operation of Nakhchivan SPP in 2016-2017 shows that the annual capacity utilization rate is about 16%. Its maximum value is 22% in July and its lowest value is 6% in December. At the same time, the maximum value of the intensity of solar radiation is observed in the afternoon (12.00-13.00) and is about 970-1000 KW/m^2.

The result

- The potential of solar energy in the NAR is 10-20% higher than in other regions of Azerbaijan, the maximum value of solar radiation density is 970-1000 KW/m^2;
- In NAR, the annual solar energy potential of 1 m2 of surface is approximately 1750-1800 KWh, and 260-350 KWh of electricity can be produced per 1 m2 of surface when the efficiency factor of the SPP is 15-20%;
- Non-agricultural areas may be selected for the construction of small solar power plants in the Nakhchivan Autonomous Republic along the Araz River valley, around the Nakhchivan-Julfa, Nakhchivan-Sharur roads, around the Nakhchivan-Shahbuz road;
- The formulas proposed as a result of the assessment of solar energy potential in the NAR can be used to assess the solar energy potential of the Aralig region of Igdir province of the Republic of Turkey.

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Работа поступила в редакцию 08.07.2021 г.

Принята к публикации 12.07.2021 г.

Ссылка для цитирования:

Novruzova S. Solar Energy Resources of Nakhchivan // Бюллетень науки и практики. 2021. Т. 7. №9. С. 69-78. https://doi.org/10.33619/2414-2948/70/06

Cite as (APA):

Novruzova, S. (2021). Solar Energy Resources of Nakhchivan. *Bulletin of Science and Practice, 7*(9), 69-78. https://doi.org/10.33619/2414-2948/70/06