IRSTI 34.35.01 https://doi.org/10.26577/EJE202582104

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ASSESSMENT OF SOLAR ENERGY POTENTIAL IN ZANGILAN, KALBAJAR AND QUBADLI DISTRICTS OF AZERBAIJAN ON THE SPRING EQUINOX

This article considers the main problems contributing East Zangezur, a region of strategic and ecological significance in Azerbaijan, has emerged as a focus of large-scale restoration efforts following its liberation. Comprising Jabrayil, Kalbajar, Lachin, Gubadli, and Zangilan districts, the district boasts diverse natural resources, including forests, rivers, and fertile soils. Despite the damage inflicted during the occupation, substantial progress is being made to restore the ecological balance, including forest regeneration, water purification, and renewable energy initiatives. This study emphasizes the solar energy potential of Zangilan, Kalbajar, and Gubadli districts, highlighting their geographical advantages and year-round sunlight availability. Detailed calculations of solar radiation and zenith angles on March 20th 2024 demonstrate the viability of solar projects in these areas. The findings underscore East Zangezur's renewable energy prospects and its role in Azerbaijan's sustainable development strategy.

Key words: East Zangezur, sustainable development, renewable energy, solar energy potential, solar panel installations.

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Әзірбайжан қаласының Зәңгілан, Қалбажар және Құбадлы ауданындағы күн энергиясының әлеуетін бағалау

Бұл мақалада Әзірбайжанның стратегиялық және экологиялық маңызы бар аймағы болып табылатын Шығыс Зәңгезүрді азат еткеннен кейін ауқымды қалпына келтіру жұмыстарының ошағы ретінде пайда болған негізгі проблемалар қарастырылады. Жабрайыл, Қалбажар, Лачын, Ғұбадлы және Зәңгілан аудандарын қамтитын аймақ ормандары, өзендері және құнарлы топырақтары сияқты алуан түрлі табиғи ресурстарға ие. Оккупация кезінде келтірілген залалға қарамастан, экологиялық тепе-теңдікті қалпына келтіруде, соның ішінде ормандарды қалпына келтіру, суды тазарту және жаңартылатын энергия бастамалары бойынша айтарлықтай жетістіктерге қол жеткізілді. Бұл зерттеу Зәңгілан, Қалбажар және Құбадлы аудандарының күн энергиясының әлеуетіне баса назар аударып, олардың географиялық артықшылықтары мен жыл бойы күн сәулесінің қолжетімділігін көрсетеді. 2024 жылдың 20 наурызында күн радиациясының және зенит бұрыштарының егжей-тегжейлі есептеулері бұл аймақтардағы күн жобаларының өміршеңдігін көрсетеді. Қорытындылар Шығыс Зәңгезүрдің жаңартылатын энергия перспективалары мен оның Әзірбайжанның тұрақты даму стратегиясындағы рөлін атап көрсетеді.

Түйін сөздер: Шығыс Зәңгезүр, тұрақты даму, жаңартылатын энергия, күн энергиясының әлеуеті, күн батареялары қондырғылары.

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Оценка потенциала солнечной энергии в Зангиланском, Кельбаджарском и Кубадлинском районах Азербайджана в период весеннего равноденствия

В этой статье рассматриваются основные проблемы, способствующие Восточному Зангезуру, региону стратегического и экологического значения в Азербайджане, который стал центром крупномасштабных восстановительных работ после его освобождения. Включающий Джебраильский, Кельбаджарский, Лачинский, Губадлинский и Зангиланский районы, регион может похвастаться разнообразными природными ресурсами, включая леса, реки и плодородные почвы. Несмотря на ущерб, нанесенный во время оккупации, достигается значительный прогресс в вос-

становлении экологического баланса, включая инициативы по восстановлению лесов, очистке воды и возобновляемым источникам энергии. В этом исследовании представляется потенциал солнечной энергии Зангиланского, Кельбаджарского и Кубадлинского районов, подчеркиваются их географические преимущества и круглогодичная доступность солнечного света. Подробные расчеты солнечной радиации и зенитных углов 20 марта 2024 г. демонстрируют жизнеспособность солнечных проектов в этих районах. Результаты подчеркивают перспективы возобновляемой энергии Восточного Зангезура и ее роль в стратегии устойчивого развития Азербайджана.

Ключевые слова: Восточный Зангезур, устойчивое развитие, возобновляемая энергия, потенциал солнечной энергии, установка солнечных панелей.

Introduction

East Zangezur is a historical and geographical region located in western Azerbaijan, covering the eastern part of the Zangezur mountain range. This area is one of the important regions of the country with its strategic location, natural resources and ancient cultural heritage. After the liberation of East Zangezur from occupation, large-scale restoration work has begun here.

The total area of the region is approximately 7,748 square kilometers and includes five main districts: Jabrayil, Kalbajar, Lachin, Gubadli and Zangilan. Each district has its own unique natural and geographical features. The area is known for its mountainous terrain, dense forests, rich water resources and biological diversity.

Forests are the main ecological wealth of East Zangezur. The mountain-forest landscape, especially in the Kalbajar and Lachin districts, is of great importance for the natural balance of the region. However, during the occupation, these forests were seriously destroyed by illegal logging and fires. As a result, soil erosion increased, and the habitat of rare plant and animal species was disrupted [1].

East Zangezur is also rich in water resources. Rivers such as Hakari, Okchuchay and Basitchay flow through the region. These rivers are important both as a source of drinking water and for agriculture and industry. However, during the occupation, industrial waste was discharged into these rivers by Armenia. In particular, a high concentration of heavy metals (mercury, zinc, cadmium) was found in Okchuchay, which seriously damaged the flora and fauna of the river [2].

The soils of the region are highly productive. However, during the occupation, the soils were contaminated with heavy metals and other chemicals. This created difficulties for agriculture and disrupted the ecological balance of the region.

The unique ecosystem of East Zangezur is home to rare flora and fauna. The Caucasian leopard, mountain goat and other rare animal species live here. However, illegal hunting and destruction of the ecosystem have reduced the population of these species.

After liberation from occupation, large-scale measures are being taken by the Azerbaijani government to improve the ecological situation of the region. Special projects are being implemented to restore forests, clean up polluted water bodies and protect natural resources. At the same time, work is being carried out to use alternative energy sources and develop ecotourism.

East Zangezur, with its rich natural resources and strategic location, is one of the most promising regions of Azerbaijan in economic and ecological terms. Solving ecological problems and ensuring sustainable development are one of the main conditions for fully revealing the potential of this region.

The East Zangezur region stands out as one of Azerbaijan's primary economic and geographical zones with significant renewable energy potential. Its favorable natural and climatic conditions make it well-suited for the production of solar, wind, hydro, biomass, and geothermal energy. Each energy type contributes substantially to regional economic progress and energy security [3].

Zangilan district is located in the south-western part of Azerbaijan and is an important area in terms of solar energy potential. The terrain characteristics and geographical position of the district allow for a high level of solar radiation, which increases the interest in the production of solar energy. In this article, the solar radiation potential of Zangilan district will be analyzed, and information will be provided about favorable conditions for the use of solar energy and energy production in the region.

Solar radiation refers to the amount of energy reaching the earth's surface from the sun and is

largely related to the length of the day, weather conditions, and geographic location. The annual average value of solar radiation for Zangilan district ranges from 1,600 kWh/m² to 1,800 kWh/m². This is an indicator that provides ideal conditions for the production of solar energy [4].

Zangilan district is characterized by numerous sunny days, especially in spring and summer. The district has 250-280 days of sunshine per year, which is very favorable for increasing the efficiency of solar panels. The high number of sunny days is one of the main factors that ensure the constant production of solar energy.

Since Zangilan district is located in the southwest, the influence of solar radiation on this area is high. Being close to the equator increases the intense influence of the sun for most of the year. Mountainous and plain areas of the district are met with different degrees of strong solar radiation. Flat areas are more suitable for installing solar panels because these areas allow better reception of the sun's rays.

The annual distribution of solar radiation in Zangilan district is different in different seasons. The radiation level is at its highest during the spring and summer months, when solar panels can provide maximum energy production. In winter and autumn, the amount of radiation decreases, but this period also retains a certain potential for solar energy production [5].

Kalbajar district is located in the western part of Azerbaijan, in a high mountainous area with significant strategic importance. The district lies within the Karabakh mountain range and shares borders with Lachin district to the east and Armenia to the west. The total area of the district is 3,054 square kilometers, with an average elevation ranging between 1,500 and 2,000 meters above sea level [6].

The geographic location of Kalbajar provides access to abundant natural resources, including water reserves. The Tartar River, Bazarchay, and their tributaries traverse the region, making it one of the richest areas in terms of water resources in Azerbaijan. These rivers are vital for hydroelectric power generation and agricultural irrigation. The district is also known for its mineral springs, thermal waters, and medicinal water sources, contributing to its potential for health tourism and economic development.

Kalbajar has a mild mountain climate, characterized by cool summers and cold winters. The average annual temperature ranges between 6-10°C, with significant snow cover during winter months. Annual precipitation varies from 600 to 800 millimeters, which enhances the district's water reserves and supports year-round river flow. The mountainous terrain plays a crucial role in shaping the climate, creating favorable conditions for both renewable energy projects and agricultural activities [7].

Gubadli is a strategically significant district located in the southwestern part of Azerbaijan. Established in 1930, it covers an area of 802 square kilometers. The district shares borders with Lachin to the north, Khojavend to the northeast, Jabrayil to the east, and Armenia to the south and west. The area is predominantly mountainous, situated in the southern part of the Zangezur mountain range. One of the highest peaks in the district is Mount Garachig.

Gubadli experiences a moderate warm mountain-steppe climate, characterized by hot and dry summers and relatively mild winters. The average annual temperature ranges between 10-12°C, while annual precipitation amounts to 600-800 mm, mainly occurring in spring and autumn. In the mountainous areas, a snow cover forms during the winter months, which plays a crucial role in replenishing the district's water resources [8].

Gubadli is rich in natural resources. Approximately 20-25% of its territory is covered with forests, consisting of oak, walnut, elm, and other valuable tree species. The district is home to diverse wildlife, including deer, mountain goats, bears, foxes, and various bird species.

The district also has significant potential for agriculture. Fertile plains are suitable for crop cultivation, while forest resources and pastures support livestock farming.

Gubadli is abundant in water resources. The main rivers flowing through the district are the Hakari River and the Bargushad River, which are vital for agricultural irrigation and hydroelectric energy production. The district also has numerous springs and freshwater sources, which provide drinking water and support various economic activities [9].

Gubadli holds a significant position in Azerbaijan’s renewable energy strategy. Its

geographical location and natural conditions create favorable opportunities for the development of alternative energy sources, including solar, wind, hydro, and biomass energy.

Solar Energy – With 2,500-2,800 hours of annual sunlight, Gubadli is well-suited for solar power projects. The implementation of solar energy systems can significantly contribute to the region's energy sustainability.

Wind Energy – The mountainous terrain and frequent winds make the district ideal for wind power generation. Wind turbines can be installed in high-altitude areas to produce clean, renewable energy.

Hydropower – The steady flow of the Hakari and Bargushad rivers provides an excellent opportunity for the construction of small hydropower plants, which could enhance the district's energy infrastructure.

Biomass Energy – Forest resources, agricultural waste, and organic materials in Gubadli can be used to produce biomass energy. This approach not only offers an alternative energy source but also ensures effective waste management [10].

Gubadli is not only a district of natural and historical significance but also a strategically vital area. Liberated from occupation during the 2020 Patriotic War, the district is now undergoing extensive reconstruction and redevelopment. Significant investments are being made in modern infrastructure projects, renewable energy development, and environmental conservation [11].

The district's geographical location, abundant natural resources, and renewable energy potential are expected to make substantial contributions to Azerbaijan's economic growth and energy security. The ongoing restoration efforts will transform Gubadli into a thriving region, ensuring its integration into the country's broader development framework [12].

Materials and methods

Zangilan district has high potential for solar energy production. The vast plains of the district provide ideal conditions for the construction of solar power stations. In particular, the use of solar energy is proposed to meet the energy needs of Zangilan's agricultural and industrial sectors. Installing solar panels will help protect the environment, reduce energy costs and ensure energy independence [13].

To calculate the solar radiation and solar energy production for March 20th 2024, we need to calculate the following parameters: declination (δ), sun angles, and other factors. Let's go through these steps [14]:

1. Declination (δ) – March 20th 2024.

The solar declination angle represents the angle at which the sun's rays strike the Earth, varying throughout the year based on Earth's position in its orbit. To calculate the solar declination angle, the following formula is used [15]:

$$\delta = 23.44° \times \sin\left(\frac{360°}{365} \times (N + 10)\right) \quad (1)$$

Where:

N is the day of the year. For March 20, N = 79 since it is the 79th day of the year.

23.44° represents the Earth's maximum tilt relative to its orbital plane.

Using the formula for March 20 2024:

$$\delta = 23.44° \times \sin\left(\frac{360°}{365} \times (79 + 10)\right)$$

$$\delta = 23.44° \times \sin(87.6°)$$

$$\delta = 23.44° \times 0.998 \approx 23.34°$$

Therefore, the solar declination angle on March 20 is approximately 23.34°.

2. Calculation of Solar Hour Angle (H):

The solar hour angle H represents the position of the sun relative to a given meridian at a specific time of day. The formula 2 to calculate the hour angle is [16]:

$$H = 15° \times (T - 12) \quad (2)$$

Where:

T is the time of day in hours.

For this calculation, we will use T = 12, which corresponds to 12:00 PM.

$$H = 15° \times (12 - 12) = 0°$$

Thus, at 12:00 PM, the hour angle is 0°.

3. Calculation of Zenith Angle (θ):

The zenith angle represents the angle between the sun and a point directly overhead (zenith). To calculate the zenith angle, the formula 3 is used [17]:

$$\theta = \arccos(\sin(\varphi) \times \sin(\delta) + \cos(\varphi) \times \cos(\delta) \times \cos(H)) \quad (3)$$

Where:

ϕ is the geographic latitude of the location, which for Zangilan is 39.4°.

δ is the solar declination angle, which we calculated as 23.34°.

H is the solar hour angle, which is 0°.

Substituting into the formula [18]:

$$\theta = \arccos(\sin(39.4°) \times \sin(23.34°) + \cos(39.4°) \times \cos(23.34°) \times \cos(0°)) = 16.2°$$

Thus, the zenith angle on March 20 2024 at 12:00 PM is approximately 16.2°.

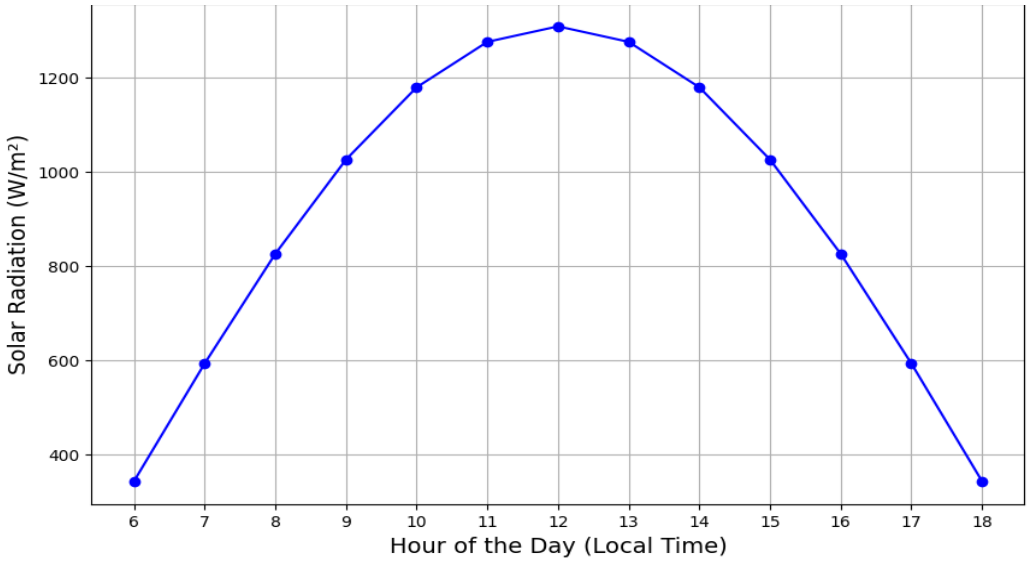

Figure 1 – Solar radiation in Zangilan on March 20 2024

4. Calculation of solar radiation (Ed):

Solar radiation is the amount of energy received per unit area from the sun. To calculate the solar radiation, we use the base value of solar radiation G_0 = 1361 W/m², and the zenith angle θ we just calculated.

The formula 4 to calculate solar radiation is [19]:

$$Ed = G_0 \times cos(\theta) \quad (4)$$

Where:

G_0 is the base value of solar radiation, which is 1361 W/m².

θ is the zenith angle, which we found to be 16.2°.

Calculating the solar radiation:

$$Ed = 1361 \times 0.961 = 1309.5\ W/m^2$$

Thus, the solar radiation in Zangilan on March 20 at 12:00 PM is approximately 1309.5 W/m².

Kalbajar's renewable energy resources align with Azerbaijan's long-term energy security strategy. Utilizing hydropower, solar, wind, and biomass energy can help reduce reliance on fossil fuels while improving the region's environmental sustainability. Renewable energy development also plays a key role in fostering economic growth and creating job opportunities in the region.

1. Solar Radiation Analysis for Kalbajar on March 20 2024

To analyze the solar radiation in Kalbajar on March 20, we follow similar steps as for Zangilan, adjusting the calculations based on Kalbajar's latitude.

The geographical latitude of Kalbajar is approximately 40.1°.

2. Solar Declination Angle (δ)

The solar declination angle represents the tilt of the Earth's axis relative to the sun. For March 20:

$$\delta = 23.44° \times \sin\left(\frac{360°}{365} \times (79 + 10)\right) = 0$$

Where:

79 is the day of the year (March 20 is the 79th day).

The Earth's axial tilt is 23.44°.

Substituting into the formula:

$$\delta = 23.44° \times 0.998 \approx 23.34°$$

Thus, the solar declination angle is approximately 23.34°.

3. Solar Hour Angle (H)

The solar hour angle determines the sun's position relative to the observer's meridian. For noon (12:00 PM):

$$H = 15° \times (12 - 12) = 0°$$

Thus, the hour angle is 0°.

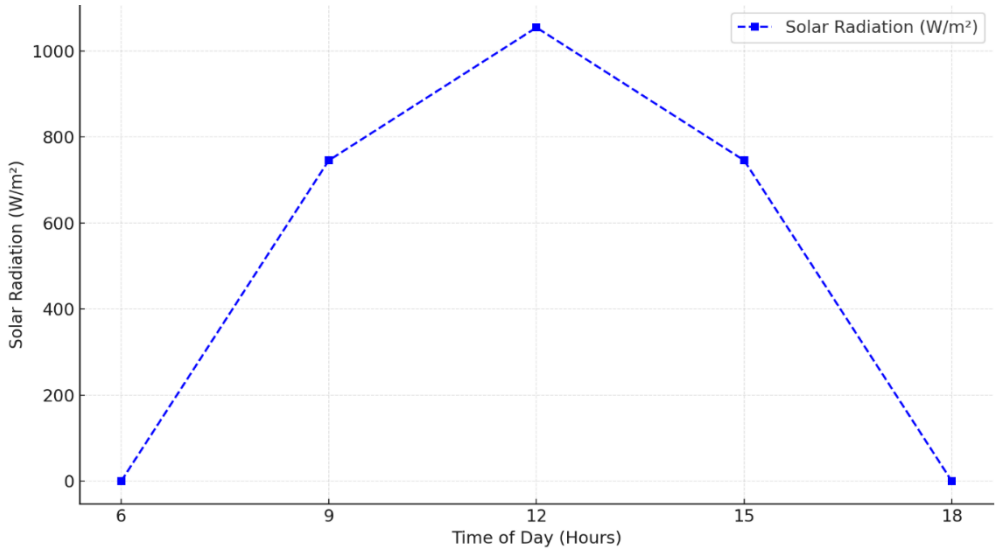

Figure 2 – Solar radiation in Gubadli on March 20 2024

4. Zenith Angle (θ)

The zenith angle represents the angle between the sun and the vertical line overhead. The formula is:

$$\theta = \arccos(\sin(40.1°) \times \sin(23.34°) + \cos(40.1°) \times \cos(23.34°) \times \cos(0°)) = 17.3°$$

Thus, the zenith angle is approximately 17.3° at 12:00 PM.

5. Solar Radiation (Ed)

Solar radiation is calculated using the base solar constant G_0 = 1361 W/m² and the zenith angle:

$$Ed = 1361 \times \cos 17.3°$$
$$Ed = 1361 \times 0.955 = 1299.2\ W/m^2$$

Thus, the solar radiation in Kalbajar on March 20 at 12:00 PM is approximately 1299.2 W/m².

Solar Radiation and Zenith Angle Calculation for Gubadlı on March 20th 2024 (Table).

- Latitude (ϕ): 39.2° (Qubadli region's approximate geographical latitude).
- Solar Declination (δ): 0° (corresponds to the spring equinox).
- Solar Constant (G_0): 1361 W/m^2 (average solar energy reaching the Earth).
- Hour Angles (H): These represent the Sun's position at different times of the day

Table – Hourly Results for March 20th

Time (Hours)	Hour Angle (H)	Zenith Angle (θ)	Solar Radiation (E_d) (W/m^2)
6:00 AM	−90°	108.05°	0
9:00 AM	−45°	70.39°	465.36
12:00 PM	0°	39.2°	1057.40
3:00 PM	45°	70.39°	465.36
6:00 PM	90°	108.05°	0

- At 6:00 AM and 6:00 PM, the Sun is at a low position, leading to a zenith angle exceeding 90°. Thus, no direct solar radiation reaches the surface.
- At 12:00 PM, the Sun is at its highest point with a zenith angle of 39.2°.
- Peak radiation of 1057.40 W/m^2 occurs at solar noon.
- Morning and evening radiation values are significantly lower due to the higher zenith angle.

Errors:

When considering an ±0.5° error in the zenith angle (θ) calculation, it affects the results and can cause a ±5 W/m² variation in the solar radiation value. Let's explain this in detail:

There can be a ±0.5° error in measuring the zenith angle. This will change the position of the sun, and in turn, the solar radiation values.

A ±0.5° error in θ directly affects the calculated radiation value because the cos(θ) function is very sensitive to small changes in θ.

A ±0.5° error in θ can cause a ±5 W/m² change in solar radiation. This happens because the cos function changes significantly with small variations in the angle.

For example, when θ = 16.2°, a ±0.5° error means θ could range from 15.7° to 16.7°, leading to a 5 W/m² variation in the radiation value.

This error is a approximate error and should always be included in the results as error margins. Thus, when presenting the calculation, the ±5 W/m² variation should be specified to indicate the potential error in the result.

The ±0.5° error in the zenith angle results in a ±5 W/m² variation in solar radiation. This is a typical error margin that should be considered during calculations and reflected in the results to ensure the data is accurate and reliable.

Results and discussion

Gubadli, Zangilan, and Kalbajar, located in Azerbaijan, are ideal regions for solar energy development due to their geographical location, climate conditions, and solar irradiation potential. These areas receive significant sunlight throughout the year, making them suitable for renewable energy projects like solar panel installations. Below is an analysis of the energy potential and proposed installations.

To estimate energy production, we assume the installation of 1 hectare (10,000 m^2) of solar panels with an efficiency (η) of 18%. The formula 5 is used [20]:

$$P = E_d \times A \times \eta \quad (5)$$

Where,

P: Power output (W);

E_d: Solar radiation (W/m^2);

A: Panel area (m^2);

η: Panel efficiency.

Annual energy production is estimated using [21]:

$$E_{year} = P \times Annual\ Sunshine\ Hours \quad (6)$$

Assuming 2000 sunshine hours per year, the results are calculated below.

2. Solar Energy Potential Calculations [22]:

a. Kalbajar

$$P = 1299.2 \cdot 10{,}000 \cdot 0.18 = 2{,}338{,}560W = 2.34MW$$
$$Eyear = 2.34 \cdot 2000 = 4680MW/year$$

b. Zangilan

$$P = 1309.5 \cdot 10{,}000 \cdot 0.18 = 2{,}357{,}100W = 2.36MW$$
$$Eyear = 2.36 \cdot 2000 = 4720MW/year$$

c. Gubadli

$$P = 1057.4 \cdot 10{,}000 \cdot 0.18 = 1{,}903{,}320W = 1.90MW$$
$$Eyear = 1.90 \cdot 2000 = 3806.6MW/year$$

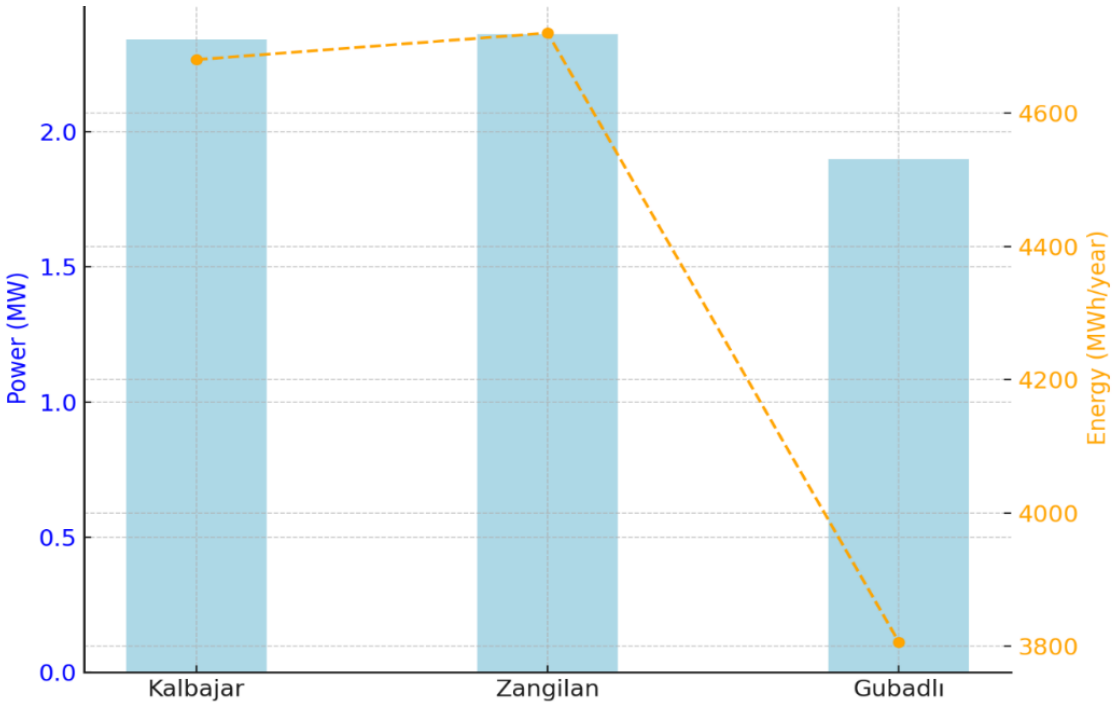

Figure 3 – Annual Solar Energy Production Potential in Kalbajar, Zangilan, and Gubadli

The regions of Kalbajar, Zangilan, and Gubadli have significant potential for solar energy production, with an estimated combined annual output of approximately 13,206.6 MW/year. Harnessing this energy will support Azerbaijan's renewable energy goals and contribute to sustainable development in these areas.

Conclusion

The regions of Zangilan, Kalbajar, and Gubadli possess significant potential for solar energy production, contributing to Azerbaijan's renewable energy strategy. The calculations were conducted for March 20 2024, which corresponds to the spring equinox. This date was chosen because the distribution of solar radiation is equal worldwide, providing a precise reference point for energy assessments. On this day, the equal length of day and night creates ideal conditions for evaluating solar energy generation potential.

Based on the research findings, the annual energy output from 1 hectare (10,000 m²) of solar panels in these regions amounts to a total of 13,206.6 MW. Zangilan (4,720 MW/year) and Kalbajar (4,680 MW/year) demonstrate higher solar radiation levels, resulting in greater energy production capacity.

Utilizing solar energy in these areas will significantly reduce greenhouse gas emissions, contributing to environmental conservation and

enhancing energy security. Additionally, this technology will lower energy costs and stimulate economic development in the regions. The study highlights that the installation of solar panels in Zangilan, Kalbajar and Gubadli not only boosts renewable energy generation but also aligns with Azerbaijan's long-term energy strategy. These initiatives support sustainable economic growth and play a pivotal role in fostering environmental sustainability.

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Поступила 10 декабря 2024 года
Принята 10 марта 2025 года