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Original paper

Ecoenergy Potential of a Solar-Wind Station in the Khazar Nature Reserve in the Caspian Sea

A. M. Penjiyev *, B. M. Mamedov

Turkmen State Institute of Architecture and Civil Engineering, Ashgabat, Turkmenistan

* *e-mail: ampenjiyev@gmail.com*

Abstract

The article considers solar and wind energy resources and their ecological potential in the Khazar Reserve on Ogurchinsky Island in the Caspian Sea. The methodological basis is formed by the empirical calculations for the preparation of a feasibility study and the creation, development and implementation of energy-efficient technologies based on solar-wind energy equipment in the Reserve. The paper provides an energy, economic and ecological assessment of a solar power station with a capacity of 10 kW·h/day based on theoretical and methodological calculations and taking into account natural and climatic conditions. The station generates electricity (3658.34 kW·h/year), saves organic fuel (1463.336 kg of equivalent fuel) and reduces harmful emissions into the biosphere: SO_2 (30.41 kg), NO_x (16.38 kg), CO (2.13 kg), CH_4 (4.47 kg), CO_2 (2339.64 kg), solids (3.19 kg). One 400 W wind turbine can generate 19.45 kW·h/m^2·year, or an average of 1.62 kW·h/m^2·month, with an equivalent reduction in fuel consumption of 7.78 equivalent fuel. The obtained scientifically substantiated results will contribute to the improvement of social, living, economic and environmental conditions of the island's inhabitants, the conservation of bioresources, and strengthening energy and environmental security. The results of the feasibility study will help implement various solar-wind technological complexes in the region.

Key words: solar-wind energy resources, environmental potentials, mathematical statistics, Khazar Reserve, Ogurchinsky Island, Caspian Sea

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Экоэнергетический потенциал солнечно-ветровой станции в Хазарском заповеднике в Каспийском море

А. М. Пенджиев *, Б. М. Мамедов

Туркменский государственный архитектурно-строительный институт, Ашгабат, Туркменистан

* *e-mail: ampenjiyev@gmail.com*

Аннотация

Рассмотрены солнечно-ветровые энергоресурсы и их экологический потенциал в Хазарском заповеднике на острове Огурчинском в Каспийском море. Методологической основой послужили эмпирические расчеты для составления технико-экономического обоснования и создания, разработки и внедрения энергоэффективных технологий на основе солнечно-ветрового энергооборудования в заповеднике. На основе теоретических и методических расчетов и с учетом природно-климатических условий дана энергетическая, экономическая и экологическая оценка солнечной энергетической станции мощностью 10 кВт·ч/сут. Станция вырабатывает электроэнергию – 3658.34 кВт·ч/год, экономит органическое топливо – 1463.336 кг у. т. и сокращает вредные выбросы в биосферу: SO_2 – 30.41 кг, NO_x –16.38 кг, CO – 2.13 кг, CH_4 – 4.47 кг, CO_2 – 2339.64 кг, твердых веществ – 3.19 кг. С помощью одной ветроустановки мощностью 400 Вт можно получить 19.45 кВт·ч/м^2·год электроэнергии (в среднем 1.62 кВт·ч/м^2·мес.), при этом эквивалент сокращения расхода топлива составит 7.78 кг у. т. Полученные научно обоснованные результаты можно использовать для улучшения социально-бытовых, экономических и экологических условий обитателей острова, сохранения биоресурсов и укрепления энергетической и экологической безопасности. Результаты технико-экономического обоснования помогут внедрению различных солнечно-ветровых технологических комплексов в регионе.

Ключевые слова: солнечно-ветровые энергоресурсы, экологический потенциал, математическая статистика, Хазарский заповедник, остров Огурчинский, Каспийское море

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Introduction

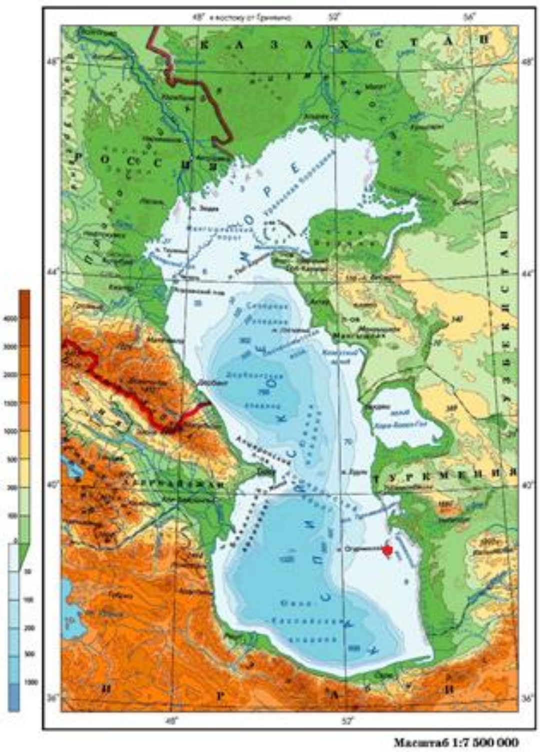
Addressing the challenge of providing energy to protected areas and pastoral farms in the Karakum Desert, which are distant from centralized power grids, necessitates evaluating the potential of renewable energy sources (RES). This effort is also motivated by global climate change concerns and the need to enhance social, economic, and environmental conditions in remote regions of Turkmenistan. Transitioning to RES will reduce reliance on fossil fuels, thereby promoting ecological sustainability and preserving biodiversity [1].

Turkmenistan is undertaking all necessary measures to address this critical issue and is implementing comprehensive mechanisms in collaboration with international organizations to ensure environmental and technological sustainability. This was emphasized by the President of Turkmenistan during speeches at the 78th session of the United Nations General Assembly and the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change.

Turkmenistan has eight state nature reserves (Repetek, Badkhyz, Kopetdag, Syunt-Khasardag, Kaplankyr, Amudarya, Koitendag, and Khazar) and 14 wildlife sanctuaries, covering a total area of 2.0 million ha, or 4% of the country's territory.

The Khazar Nature Reserve spans 270,000 ha, primarily located in the Caspian Sea. It supports over 600 plant species and hosts 466 bird species and 55 marine fish species, five of which are listed in the Red Book. Over 5 million birds migrate to the reserve annually for wintering. The reserve's fauna includes rare and protected species, such as the Caspian seal, long-eared hedgehog, and goitered gazelle, alongside other species like the tolai hare, reed cat, sand cat, and foxes, characteristic of the desert ecosystem [1–4].

The Khazar Nature Reserve includes Ogurchinsky Island (Fig. 1), located in the southeastern Caspian Sea in Turkmenistan (39° 6' N; 53° 6' E). As the largest sandy island in the Caspian Sea, it lies 45 km offshore and forms a narrow spit, 1–1.5 km wide and approximately 42 km long, extending from north to south. Electricity on the island is provided by diesel generators, with organic fuels (diesel, gasoline, kerosene, and liquefied gas) imported by sea, incurring substantial financial costs [1)] [5–7]. The use of diesel fuel results in the emission of pollutants into the environment.



F i g . 1 . Location of Ogurchinsky Island (red dot) of the Khazar Nature Reserve in the Caspian Sea [6, 7]

[1)] Gidrometeoizdat, 1989. [*Scientific and Applied Reference Book on the Climate of the USSR*]. Leningrad: Gidrometeoizdat. Series 3. Long-Term Data. Parts 1–6, 502 p. (in Russian).

Systematic measures to ensure the island's energy supply and enhance its economic, food, water, and environmental security can be achieved using renewable energy sources, specifically solar and wind power plants integrated with modern "green" technologies. These measures will also support the conservation of the region's biodiversity. Currently, energy provision in protected areas is limited: electricity is generated by low-capacity gasoline generators, and heating relies on liquefied gas.

A primary drawback of using gasoline-powered generators in protected areas is the significant noise they generate, audible from a distance of 5–10 km, which disturbs the wildlife inhabiting these regions. Additionally, the combustion of fuel emits pollutants into the environment.

The technical limitations of gasoline and diesel generators include a short engine lifespan (600–1,500 h) and high fuel consumption (350–500 g/kW·h). These generators are unable to handle heavy electrical loads and are unsuitable for round-the-clock operation to power household, laboratory, and other electrical appliances [2, 3, 8]. Consequently, a key requirement for modern autonomous power sources is the ability to provide consistent, 24-hour power supply to consumers. Currently, the condition of existing power stations, which rely on gasoline and diesel generators, is considered unsatisfactory due to severe equipment wear and tear.

These limitations can be addressed by deploying solar and wind power stations, tailored to local energy resources, thereby reducing the environmental impact of diesel and gasoline power stations. All of the above makes solving this problem undoubtedly *relevant*.

The most energy-efficient option is to use the solar and wind energy potential of the Khazar Nature Reserve on Ogurchinsky (Ogurjaly) Island in the Caspian Sea. However, implementing solar and wind energy technologies requires developing detailed design and cost estimation documentation, along with a feasibility study (FS) to assess their applicability [1–3].

Degree of development of the topic. The field of solar and wind energy has been advanced by the contributions of prominent scientists, including V.A. Baum, P.P. Bezrukikh, V.I. Vissarionov [2)], V.M. Evdokimov, D.S. Strebkov, R.B. Bayramov, V.P. Kharitonov, U.A. Bekman, D.A. Duffy, J. Twidell, A. Angstrom, M. Jin, H.L. Wigley, and others [3)] [3, 9–15].

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2) Vissarionov, V.I., ed., 2008. [*Solar Power*]. Moscow: Izdatelskiy Dom MEI, 276 p. (in Russian).

3) Vasilev, Yu.S., Bezrukikh, P.P., Elistratov, V.V. and Sidorenko, G.I., 2008. *Estimates of Renewable Energy Resources in Russia.* Saint Petersburg: Izd-vo Politekhn. Un-ta, 250 p. (in Russian).

Turkmen scientists have made significant contributions to the field of solar energy use, achieving notable scientific and practical results. However, the main limitation of this research is its failure to account for the influence of natural and climatic factors, as well as the lack of systematic assessments of solar and wind energy resources, including their technical, economic, and ecological potential.

An analysis of literature sources indicates that the Caspian Sea region and the islands of Turkmenistan possess significant RES. However, existing scientific studies lack assessments of energy efficiency, fail to evaluate economic feasibility, and overlook environmental priorities [2), 3)] [3–5, 9–15].

Based on the analytical studies of solar and wind energy technologies, the goals and objectives for researching the energy resource potential of solar and wind energy in the Khazar Nature Reserve have been established.

The purpose of this study is to systematically evaluate the solar and wind energy potential through innovative computational methods and to assess the energy, economic, and environmental viability of developing and implementing renewable energy technologies in the region under study.

The objective of this study is to summarize and evaluate the technical, economic, and ecological potential of solar and wind power plants on Ogurchinsky Island in the Khazar Nature Reserve, focusing on energy efficiency, fuel savings, and environmental impact. It aims to apply innovative computational methods to systematically assess the energy productivity of converting solar radiation into electrical and thermal energy, determine the basic wind energy potential, and develop regression equations to forecast energy resources for the preparation of a FS.

The subject of the study is the energy efficiency and environmental sustainability of solar and wind power installations on Ogurchinsky Island.

The scientific novelty of the research lies in the development of a systematic methodology for calculating energy efficiency, incorporating natural and climatic conditions and the application of solar and wind energy technologies. Additionally, it involves evaluating the economic and environmental potential of the Khazar Nature Reserve for implementing these technologies on Ogurchinsky Island and preparing a FS.

Research methodology and methods

The methodology and research methods employ a systematic approach, integrating theoretical and practical assessments of solar and wind energy technologies to support the conservation of the island’s rich biodiversity and biological resources. The methodological framework includes empirical calculations for the preparation of a FS and the development and implementation of energy-efficient technologies based on solar and wind energy systems for farms in the region under study [2), 3)] [3–5, 14].

Meteorological characteristics of the island

The energy resources of direct solar radiation reaching a horizontal surface under clear skies in Turkmenistan throughout the year range from 1,699.4 to 1,793.0 kW·h/(m²·year) (146–154 kcal/cm²), while diffuse solar radiation under clear skies ranges from 372.3 to 453.0 kW·h/(m²·year) (32–39 kcal/cm²). On cloudy and overcast days, direct solar radiation decreases from 35 to 27%, with the diffuse component increasing to 25–40%. Across Turkmenistan, total solar energy varies from 1,687.7 to 1,897.2 kW·h/(m^2·year) (145–163 kcal/cm^2). The monthly distribution of the gross energy, technical, and economic potential of solar energy per square meter of surface area [1)] is presented in Fig. 2 [3–7].

As shown in Fig. 2, the island's solar energy resource potential ranges from 44 to 50 kW·h/(m²·month), with total solar radiation on a horizontal surface amounting to 1,685.4 kW·h/(m²·year) and an average monthly radiation of 140.45 kW·h/(m²·month). The annual sunshine duration on the island is 2,668 h, with an average monthly sunshine duration of 222.3 h. In July, the sun rises at 4:44 and sets at 19:16, and in January, it rises at 7:05 and sets at 16:55 [1)] [3, 4, 8].

The temperature regime on the island varies seasonally. The average annual temperature ranges from 4.0 to 27.9°C. From May to October, the average temperature remains around 20.0°C, gradually decreasing to 17.5°C. In January, it reaches

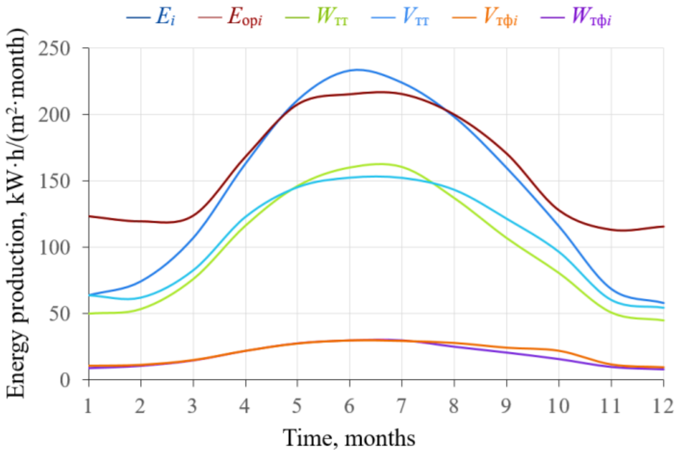


Fig. 2. Distribution of solar energy resource potentials: gross E_{opi} and technical E_i, converted into thermal $W_{тт}$ and electrical energy $W_{тфi}$ specific production into thermal $V_{тт}$ and electrical $V_{тф}$ energy on the territory of the island by month during the year

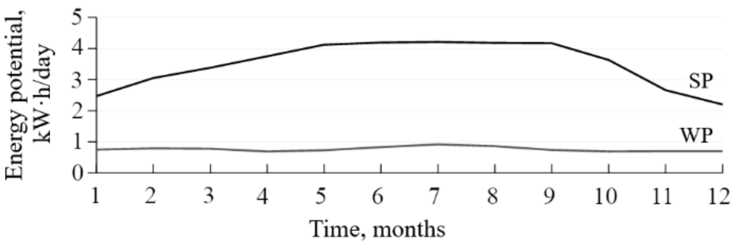
a minimum of 4.0°C. Climatic data indicate that the maximum average air temperature in January is 11.0°C, rising to 31.1°C in July. The minimum temperature drops to −0.4°C in January and rises to 23°C in July, with an average annual temperature of 11.0°C [1)] [3–7].

Wind resources. The extensive meridional extent of the Caspian Sea and the variety of atmospheric phenomena and circulation patterns result in a complex wind regime and uneven water temperature distribution on the island. These characteristics are influenced by variations in natural and climatic conditions, synoptic situations, atmospheric phenomena, air temperature, and current direction, leading to fluctuations in wind speed [1)] [3–5, 8, 9].

Scientific research indicates that storm wind formation is influenced by terrain characteristics and atmospheric circulation patterns. The average wind speed on the island ranges from 2.4 to 4.6 m/s, with an annual average of 3.3 m/s. Storm winds exceeding 25 m/s have been recorded. The wind rose [1)] in the bay varies seasonally, driven by changes in atmospheric air circulation [3, 4, 16, 17].

Fig. 3 presents the average daily distribution of wind and solar energy potential by month of the year for Ogurchinsky Island.

Wind directions in the Khazar Nature Reserve are influenced by atmospheric circulation and water temperature, ranging from 3% south to 26% west, with prevailing winds from the west (26%), northwest (16%), northeast (15%), and southwest (14%) [1)].



F i g . 3 . Average daily distribution of wind (WP) and solar (SP) energy potentials on Ogurchinsky Island by month of the year

Methodology for researching ecoenergy resources

The calculation of solar energy potential was based on the methods [2)] described in [3–5, 12–16], adapted to the conditions of the Caspian region. As previously noted, no studies to date have utilized new methods that incorporate natural and climatic conditions, hydrometeorological factors, and assessments of technical, economic, and environmental indicators for regions in Turkmenistan [8–11].

To assess the solar energy potential on the island, long-term meteorological data were considered, including sunshine duration; angles of incidence on inclined and perpendicular surfaces; hourly solar angles; solar movement parameters (declination relative to inclined surfaces and the horizon, sunrise and sunset times);

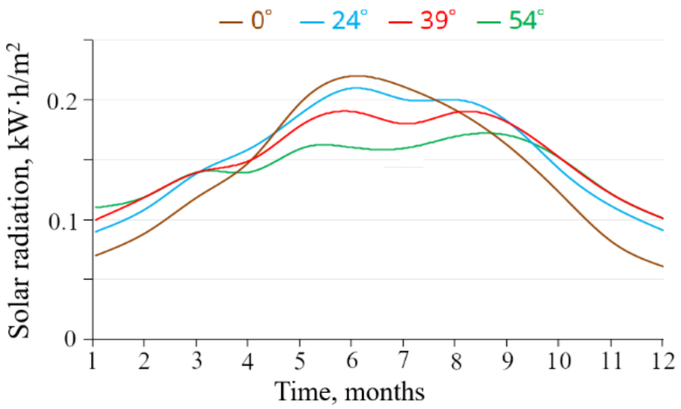
characteristics of diffuse radiation and albedo; and average monthly and annual outdoor air and surface temperatures for an operational solar power plant. Additionally, specific energy parameters of the solar power plant and local climatic factors were incorporated.

To develop physical and mathematical models, certain assumptions were adopted: Ogurchinsky Island is regarded as an area with intense solar radiation reaching the surface, geographical and climatic conditions are assumed to be uniform across the island, and average annual meteorological data for the entire island were used [3–5, 9].

Optimal tilt angle of solar converters on the island. To maximize the efficiency of solar energy technologies and installations year-round, the optimal tilt angle of solar converters must be determined, accounting for the geographical characteristics of the installation site. The calculated optimal tilt angles for a solar receiver with an east-west orientation are 54° (−0.82930 rad) in winter, 24° (0.42418 rad) in summer, and an annual average of 39° (0.26664 rad). The energy productivity of photovoltaic modules as a function of tilt angle for Ogurchinsky Island is presented in Fig. 4 [2–4, 7, 19].

Gross solar energy potential – the average annual total solar radiation reaching Ogurchinsky Island, serving as a key energy resource.

To calculate the gross solar energy potential, long-term meteorological data on solar radiation incident on horizontal and optimally inclined surfaces were considered. These data were systematized by month (E_i, where i = 1, 2, ..., 12) [1)] [3–5, 10, 17–20].



F i g. 4. Receipt of solar radiation at different angles of inclination of the photomodule, the angles equaling 0°; 24°; 54°; 39° (the optimal angle for Ogurchinsky Island)

The calculations were performed taking into account the average cosine of the angle θ of direct solar radiation relative to the normal during a 10-hour interval – from 7:00 to 17:00 – for a photovoltaic module with an area of 0.24 m². The average annual solar radiation per unit of horizontal surface area by month under clear skies $E_{\text{op}i}$, accounting for the module area, is calculated using the formula:

$$E_{\text{op}i} = \frac{E_{\Pi i}}{\langle \cos\theta \rangle} = \frac{(1-\varepsilon)E_i}{\langle \cos\theta \rangle} = 456.2 \text{ kW·h/(m}^2\text{·month)},$$

where $E_{\Pi i}$ is the average annual direct solar radiation per unit of horizontal surface area by month, kW·h/(m²·month); E_i is the average annual total solar energy per unit of horizontal surface area by month, kW·h/(m²·month); cos θ is the average cosine of the angle of incidence of solar rays on a perpendicular surface, varying from 24° in summer to 54° in winter; ε is the radiation coefficient, ranging from 0.14 to 0.28 (with an annual average of 0.221667) [1), 2)] [3–5, 10, 14, 15]. The optimal tilt angle for the island over the year is 39°.

The total solar radiation E for a 10-hour daily interval from 07:00 to 17:00 per unit of horizontal surface area of a photovoltaic module per year is calculated as:

$$E = \sum_i E_i = 404.5 \text{ kW·h/(m}^2\text{·year)}.$$

Consequently, the gross solar radiation potential W_B per 0.24 m² of the island's area is:

$$W_B = E \cdot S_{сэс} = 404.5 \cdot 0.24 = 97.08 \text{ kW·h/year},$$

where $S_{сэс}$ is the area of the solar power plant, m².

The technical potential of total annual solar radiation is defined as the amount of energy that can be converted into usable energy in compliance with environmental standards over the course of a year. In this study, it is calculated as the sum of thermal energy obtained from solar radiation conversion for water heating using a solar collector [1), 2)] with an area of 1.58 m² and electrical energy generated by a photovoltaic module with an area of 0.24 m² [3–5, 10, 14, 15].

Technical potential for converting solar energy to heat water using a water heater. The calculations utilized the parameters of the SCH-12 vacuum solar collector, which is thermally insulated with polyurethane foam and comprises 12 vacuum tubes with 14 mm diameter copper heat pipes. The collector has an area of 1.58 m², a weight of 41 kg, and dimensions of 2000 × 950 × 1420 × 1400 mm. It is designed for year-round operation and can withstand temperatures as low as −40 °C.

The calculations also used thermal parameters, including water temperature T (60 °C); absorption intensity $F(\tau\alpha)$ (0.9); heat transfer coefficient FU_L = 0.005 kW/(m²·°C); average monthly ambient temperature T_{oi}, °C; latitude φ; declination angle δ; sunshine varying during the i-th month t_{Ci}, h/month; the number of clear and partly cloudy hours, along with operational time t_{Pi}, h/month [2), 3)] [3, 4, 12–15].

The technical potential of the solar collector $W_{\text{тт}i}$ per unit of collector area $S_т$ during the operational period from 7:00 to 17:00 is calculated as:

$$\frac{W_{\text{тт}i}}{S_{\text{т}}} = E_i F[(\tau\alpha) - U_{\text{L}}(T - T_{\text{o}i})\cos(-\delta)\frac{t_{\text{P}i}}{E_i}] = \sum_i W_{\text{тт}i} = 102.65 \text{ kW·h/(m}^2\text{·year)},$$

where $S_{\text{т}}$ is the area allocated for the heat collector, m^2; $F(\tau\alpha)$ is the absorption intensity, $F(\tau\alpha) = 0.9$; FU_{L} is the heat transfer coefficient, 0.005; $T_{\text{o}i}$ is the average monthly temperature, °C; δ is the declination angle, degrees; $t_{\text{P}i}$ is the operational duration of solar collector, h/month.

The total of solar thermal energy potential $W_{\text{тт}}$ for a 10-hour daily interval is calculated by summing the monthly contributions:

$$W_{\text{тт}} = 102.65 \cdot S_{\text{т}},$$

where $S_{\text{т}}$ is the area allocated for solar thermal installations, m^2.

The technical potential of electricity generated from the conversion of solar radiation. The calculations are based on the technical specifications of the SIM-30-12-5BB silicon monocrystalline photovoltaic module, with the following characteristics: area 0.24 m^2; length 541 mm; width 439 mm; height 25 mm; power – 30 W; cell size 156 × 55.72 mm; operating voltage 18.67 V; and operating temperature range from −40 to 85 °C.

The following photovoltaic module parameters were incorporated into the calculation formulas: temperature gradient $\chi = 0.004$ K^{-1}; temperature $T_1 = 298$ K; efficiency $\eta_1 = 0.15$; heat transfer coefficient $\lambda = 40$ W/m^2·K; and absorption coefficient $\alpha = 0.97$ [3)] [3–5, 14, 15].

The average monthly operating temperature T_i of the photovoltaic module is calculated using the formula:

$$T_i = \frac{\frac{E_i}{t_{\text{P}i}}[\alpha - \eta_1(1 + \chi T_1)] + \langle\lambda\rangle T_{\text{o}i}}{\langle\lambda\rangle - \frac{E_i}{t_{Pi}}\eta_1\chi},$$

where χ – temperature gradient, 0.004 K^{-1}; $T_{1,i}$ – temperature, 298 K; η_1 – efficiency, 0.15; λ – heat transfer coefficient, 40 W/m^2·K; α – absorption coefficient, 0.97.

The technical potential $W_{\text{тф}i}$ for each month at the optimal tilt angle of the photovoltaic module (39°) is calculated based on the area of one photovoltaic module $S_{\text{ф}}$, equal to 0.24 m^2, using the formula:

$$\frac{W_{\text{тф}i}}{S_{\text{ф}}} = E_i\eta_1[1 - \chi(T_i - T_1)] = \sum_i W_{\text{тф}i} = 42.7 \cdot S_{\text{ф}},$$

where $S_{\text{ф}}$ is the area of one photovoltaic module, m^2; T_i is the average monthly operating temperature of the photovoltaic module, K.

The total annual technical potential, $W_{\text{тф}}$, W·h/year, is calculated by summing the values across the entire area of the photovoltaic module:

$$W_{\text{тф}} = 42.7 \cdot S_{\text{ф}}.$$

The economic potential of solar energy represents the possible volume of solar radiation converted into thermal and electrical energy on Ogurchinsky Island over the course of a year, considering economic viability. The results are economically justified for this region based on current prices for energy derived from conventional sources and are expressed in tons of fuel equivalent, in compliance with environmental standards.

To calculate the economic potential of solar energy for water heating, the following parameters were used: hot water temperature $T_H = 60$ °C and cold water temperature $T_C = 15$ °C; technical characteristics of solar collectors: $F(\tau\alpha) = 0.9$; $F \cdot U_L = 0.005$ kW/(m^2·°C); water consumption rate m = 100 kg/(person·day); collector cost $C = 400$ \$/m^2; $T_{SL} = 15$ years; water heat capacity $c_p = 4.17$ kJ/(kg·°C) [3–5, 18–20].

The economic potential of solar thermal collectors installed at an optimal angle to the horizon is calculated using the formula:

$$W_{\text{ЭТ}i} = V_{\text{т}i} \cdot S_{\text{ЭТ}},$$

where $W_{\text{ЭТ}i}$ is the monthly economic potential (i = 1, 2, …, 12) (summed over all months of the year); $S_{\text{ЭТ}}$ is the economically viable area of installed thermal collectors.

The thermal energy generated from solar radiation, $V_{\text{т}i}$, is calculated as:

$$V_{\text{т}i} = E_{\text{H}i} \cdot F[(\tau\alpha) - U_L(T - T_{oi})\frac{t_{Ci}}{E_{\text{H}i}}] = \sum_i V_{\text{т}i} = 8.5 \text{ kW·h/(m}^2\text{·month)},$$

where $E_{\text{H}i}$ is the monthly solar radiation, kW·h/(m^2·year).

The specific volume of solar energy generated determines the economic viability and payback period of solar installations.

The calculated volumetric heat output of a solar water heater, heating water to a temperature of up to 44 °C (m^3/month), is presented in Fig. 5.

The economic potential of solar radiation in the region increases with the amount of energy generated per unit of surface area of the solar collector, considering three key factors: the critical value of specific heat energy output, the economic parameters of energy consumption, and the cost parameters of industrial energy production, accounting for fuel costs and regional environmental factors.

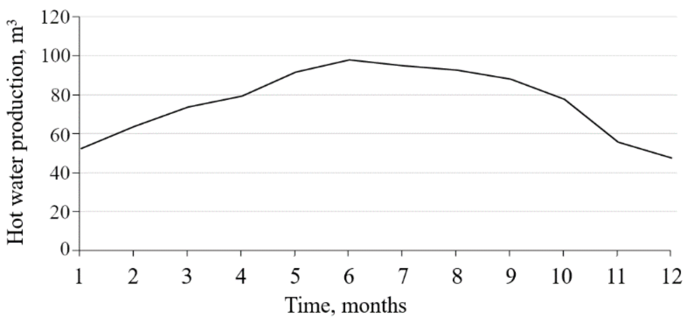


Fig. 5. Volumetric heating output of a solar water heater when heating 1 m^3 water to a temperature of 44°C by months

The calculation of the economic resource potential for obtaining electricity from the conversion of solar radiation is similarly determined by the expression:

$$W_{ЭФi} = V_{фi} \cdot S_{ЭФ},$$

$$V = E_{фi}\eta_1\left[1 - \chi\left(T_i - T_1\right)\right] = \sum_i V = 3.6 \text{ kW·h/(m}^2\text{·month)},$$

where $V_{фi}$ is the amount of energy generated per unit area of the solar battery in the *i*-th month, kW·h/(m^2·month); $S_{ЭФ}$ is the economically viable area of installed solar photovoltaic modules, m^2; $E_{фi}$ is the average annual solar energy yield per unit area of the solar battery in the *i*-th month of the year, kW·h/(m^2·month) 2), 3) [3, 13–15].

Expected economic indicators of the solar power plant (SPP): the expected electricity output of a single SPP, comprising a single photovoltaic module with an area of 5.2 m² and a capacity of 100 W, oriented south at an optimal tilt angle of 39°, is 5.01 kW·h/day or 60.4 kW·h/year. The total electricity generation for the SPP is 1829.17 kW·h/year. The estimated cost of the SPP is $6,336.96, with a profitability of 6.76%. At an electricity cost of $0.055 per kW·h, the payback period for the photovoltaic SPP is 2.8 years.

The ecological potential of solar radiation on the island contributes to the technical resource potential, which is converted into thermal, electrical, and other energy forms using technological equipment to reduce anthropogenic environmental impacts from fossil fuel use [3–5, 17].

The energy, economic, and environmental potential of a single photovoltaic module on the island yields 42.77 kW·h/year, equivalent to an average of 3.6 kW·h/month of electricity, resulting in a reduction of 17.1 kg of equivalent standard fuel consumption annually. The environmental benefits include reductions in harmful emissions as follows: SO_2 – 0.3555 kg/year; NO_x – 0.1915 kg/year; CO – 0.0248 kg/year; CH_4 – 0.0522 kg/year; CO_2 – 27.35 kg/year; and solid particles – 0.0373 kg/year.

Solar radiation is used to convert energy to heat water to 44 °C. The energy, economic, and environmental potential of this process yields 102.65 kW·h/year, equivalent to an average electricity saving of 8.5 kW·h/month, with a corresponding reduction in fuel consumption of 41.1 kg of fuel oil annually. The environmental benefits include reductions in harmful emissions as follows: SO_2 – 0.853427 kg/year, NO_x – 0.459538 kg/year, CO – 0.05968 kg/year, CH_4 – 0.125328 kg/year; CO_2 – 65.64826 kg/year, and solid particles – 0.08952 kg/year.

Wind energy potential

The HY-400L low-power wind turbine is designed for power generation. Its technical specifications are as follows: rated power of 400 W; maximum power of 500 W; rated voltage of 24 V; start-up wind speed of 2 m/s; cut-in wind speed of 2.5 m/s; rated wind speed of 12 m/s; operating temperature range of −40 to 60 °C; maximum wind speed of 50 m/s; number of blades – 5; rotor diameter – 1.55 m; swept area – 1.89 m; overall dimensions – 118 × 47 × 27 cm.

A single 5 m high wind turbine on the island can generate 19.45 kW·h/m^2/year of electricity, equivalent to an average of 1.62 kW·h/m^2/month, with a corresponding reduction in fuel consumption of 7.78 kg. The environmental benefits include reductions in harmful emissions as follows: SO_2 – 0.161706 kg/year; NO_x – 0.087073 kg/year; CO – 0.011308 kg/year; CH_4 – 0.023747 kg/year; CO_2 – 12.43895 kg/year; and solid particles – 0.016962 kg/year [3)] [3, 14–16].

According to the results of the calculations, the use of solar radiation to conserve fuel can reduce the costs of various products and their energy-intensive production processes, enhance the ecological conditions, and improve social and living standards in the Caspian region of Turkmenistan.

Statistical analysis of conditions

Regression equations can be applied when developing a FS and calculating the power requirements of heating devices, as well as determining heat losses under various climatic conditions for the construction of power stations or structures [3–5, 10–12].

When preparing design and cost estimation documentation, including FS, for the construction of solar and wind energy facilities, hydrometeorological data from the Khazar Nature Reserve, along with quantitative estimates of their distribution, are essential to support the work of engineers, cost estimators, and designers.

Hydrometeorological data were processed using mathematical statistics methods. The resulting data were approximated as a simplified scatter plot, represented by a linear regression equation in the form of a correlation ellipse. In a rectangular coordinate system, the linear regression equation is expressed as $y = a + bx$, where a represents the intercept and b denotes the regression coefficient. To analyze the impact of incident solar radiation on the energy output of a photovoltaic module, a regression equation was developed, incorporating the angle of inclination: 0° (horizontal position); 24° (summer period); 54° (winter period); 39° (optimal for the region). Additional factors considered include average, maximum, and minimum temperature regimes, sunshine duration, wind speed, cloudy day duration, precipitation, and soil temperature to forecast energy potential and calculate the coefficient of determination, which quantifies the strength and closeness of the relationship between variables. The resulting equations are presented below.

An important stage in regression analysis is establishing the mathematical relationship between the dependent variable y and the independent variable x. Consequently, the dependent variable y – representing the angle of inclination of the photovoltaic module – was determined on a horizontal surface as follows: 24° for the summer period, 54° for the winter period, and an optimal annual angle of 39°. The independent variable x corresponds to the intensity of solar radiation incident on the surface.

The following regression equations for the tilt angles of photovoltaic modules were obtained:

for 24°: $y = 0.0004x + 0.1489;\ R = 0.0012;$ (1)

39°: $y = 0.0008x + 0.1445;\ R = 0.0079;$ (2)

54°: $y = 0.0005x + 0.1385;\ R = 0.0054;$ (3)

0°: in a horizontal position

$y = -0.0007x + 0.1435;\ R = 0.0017.$ (4)

Electricity generation by a solar installation with one photovoltaic module:

$$y = -0.0098x + 3.628;\ \ R = 0.0018. \quad (5)$$

Regression equation for heat energy production by a single solar collector when heating water:

$$y = -0.0239x + 8.7094;\ \ R = 0.0018. \quad (6)$$

Hot water output, m^3:

$$y = -0.1885x + 77.435;\ \ R = 0.0015. \quad (7)$$

Electricity generation by a solar power plant with 10 photovoltaic modules with a capacity of 10 kW:

$$y = 0.0164x + 4.9286;\ \ R = 0.0026. \quad (8)$$

Regression equation and average wind speed dispersion coefficient:

$$y = -0.0038x + 3.4333;\ \ R = 0.0004. \quad (9)$$

Electricity generation by a single wind turbine:

$$y = 0.0034x + 1.5988;\ \ R = 0.0074. \quad (10)$$

Using data from scientific climate reference materials and observations from the State Meteorological Service, regression equations were derived as follows:

sunshine hours:

$$y = 0.0573x + 7.46, \quad (11)$$

duration of sunshine:

$$y = 3.3776x + 200.88, \quad (12)$$

average wind speed:

$$y = -0.007x + 5.7788, \quad (13)$$

number of cloudy days:

$$y = -0.1262x + 3.4621, \quad (14)$$

precipitation amount:

$$y = -0.4336x + 11.485, \quad (15)$$

monthly soil temperature:

$$y = 0.6538x + 12.0. \quad (16)$$

To assess the relationship between two variables, x and y, for the island over the course of a year, the following correlation coefficients R were calculated for the conversion of solar energy into electrical energy: 0.0018 for a single photovoltaic module, 0.0018 for a thermal collector, and 0.0015 for hot water production volume. These values indicate a very weak correlation [3–5, 17, 20].

Using the regression equations (1)–(16), it is possible to forecast the range of annual variations for the following parameters: electricity generation by solar and wind power plants, average wind speed, number of cloudy days, precipitation amount, average air temperature, sunshine duration, and monthly soil temperature.

Productivity of wind and solar energy converters in terms of heat and electrical energy production and reduction of harmful emissions into the environment per year on the island

Energy converter	Technical potential, kW·h per year	Fuel consumption equivalent, kg fuel equivalent per year	Substances emission, kg per year					
			SO_2	NO_x	CO	CH_4	CO_2	Solid particles
Solar power plant	42.77	17.110	0.3556	0.1915	0.0248	0.0522	27.3529	0.0373
Wind power plant	19.45	7.780	0.1617	0.0870	0.0113	0.0237	12.4395	0.0169
Water heater	102.65	41.060	0.8534	0.4595	0.0596	0.1253	65.6483	0.0895
Total	164.87	65.948	1.3707	0.7381	0.0958	0.2012	105.440	0.1437

Discussion of results

Based on research utilizing reference data and systematic theoretical and practical calculations, estimates were derived for the solar energy resource potential per square meter on Ogurchinsky Island over the course of a year, encompassing gross, technical, and economic potential converted into thermal and electrical energy. The average monthly direct solar radiation at an optimal inclination angle of 39° is 1900.5 kW·h/(m²·month), while the average annual amount of solar radiation incident on a horizontal surface over a 10-hour daily interval is 1685.4 kW·h/m².

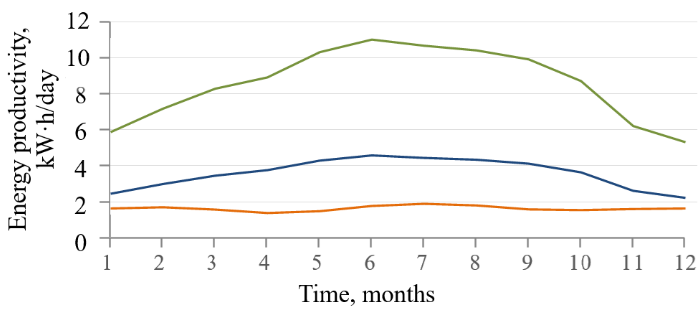
The energy efficiency, economic, and environmental potential of a Sila solar power plant (SPP) with a capacity of 30 W and an area of 0.24 m², a SCH-12 water heater (WH) with a heat output reaching 44 °C and an area of 1.58 m², and a 400 W wind power plant (WPP) are presented in the table. The table indicates that the technical potential of ten photovoltaic modules, each with an area of 0.24 m² and a capacity of 60 W, totals 42.77 kW·h/year. The ecological resource potential of solar energy for conversion into electricity corresponds to a fuel consumption reduction of 17.1 kg of fuel equivalent per year. Additionally, the technical potential of a single SCH-12 water heater with an absorption area of 1.58 m², capable of heating water to 44 °C, is 102.65 kW·h/year.

The calculated expected values for the total energy productivity of WPP and SPP, when converting solar energy into heat and electricity, amount to 164.87 kW·h/(m^2·year), with associated reductions in harmful environmental emissions per year as follows: fuel savings – 65.948 L/year, emission reductions of SO_2 – 1.3707 kg/year, NO_x – 0.7381 kg/year, CO – 0.09585 kg/year, CH_4 – 0.20129 kg/year, CO_2 – 105.4401 kg/year, and solid particles – 0.14378 kg/year 3) [9, 15, 16].

Fig. 6 illustrates the overall dynamics of the average daily energy productivity of WPP and SPP for electricity generation and thermal energy production, presented by month of the year.

The installation of 10 photovoltaic modules, each with an area of 5.2 m², on the island for laboratory research would yield the following results: an annual electricity generation of 1,829.2 kW·h, an average monthly generation of 60.4 kW·h, and an average daily generation of 5.0 kW·h/day. Monthly fuel savings would amount to 24.16 kg, with corresponding reductions in harmful emissions as follows: SO_2 – 0.502163 kg/month, NO_x – 0.270395 kg/month, CO – 0.035116 kg/month, CH_4 – 0.073744 kg/month, CO_2 – 38.62791 kg/month, and solid particles – 0.052674 kg/month.

The energy efficiency of the VSF-1 water heating system, when heating water to 44 °C, yields an annual output of 914.52 m^3/year, with an average monthly output of 76.21 m^3.



F i g . 6 . Dynamics of average daily energy productivity of renewable energy sources, solar power plants, electricity and warm water production on Ogurchinsky Island by months: orange line – wind energy production, blue line – solar energy production, green line – conversion of solar energy to heat. The numerals stand for months

To optimize the use of solar energy stations and installations throughout the year, it is essential to determine the optimal inclination angle of the solar converter based on the geographical location of the site. The calculated optimal inclination angles for a solar receiver with an east-west orientation on Ogurchinsky Island, by month, are as follows: 54° (−0.82930 rad) for winter; 24° (0.42418 rad) for summer, and an annual optimal angle of 39° (0.26664 rad).

When designing a SPP with automated solar radiation tracking based on the inclination angle for Ogurchinsky Island, the graphs in Fig. 5 [2–4, 7] can be used.

The expected environmental reduction potential for harmful emissions when using solar and wind energy technologies throughout the year on Ogurchinsky Island has been calculated as follows:

– SPP: with an annual electricity generation of 164.87 kW·h/(m^2·year), fuel savings amount to 65.948 kg of fuel equivalent/year, with emission reductions of SO_2 – 1.3707 kg/year, NO_x – 0.7381 kg/year, CO – 0.09585 kg/year, CH_4 – 0.20129 kg/year, CO_2 – 105.4401 kg/year, and solid particles – 0.14378 kg/year [3, 4, 9, 16].

– WH: with an annual output of 102.65 kW·h/(m^2·year), fuel savings amount to 41.06 kg of fuel equivalent per year, with emission reductions of SO_2 – 0.8534 kg/year, NO_x – 0.45953 kg/year, CO – 0.0596 kg/year, CH_4 – 0.1253 kg/year, CO_2 – 65.64826 kg/year, and solid particles – 0.08952 kg/year.

– WPP: with an annual electricity generation of 19.45 kW·h/(m^2·year), fuel savings amount to 7.78 kg of fuel equivalent per year, with emission reductions of SO_2 – 0.161706 kg/year, NO_x – 0.087073 kg/year, CO – 0.011308 kg/year, CH_4 – 0.023747 kg/year, CO_2 – 12.43895 kg/year, and solid particles – 0.016962 kg/year.

The results, obtained using mathematical statistics methods for regression equations (1)–(16), are essential for implementing solar-wind energy complexes and power plants in the southern sector of the Caspian Sea.

Conclusion

The energy resources of solar radiation, along with their technical, economic, and environmental potential, have been evaluated based on the hydrometeorological and natural climatic conditions of the Khazar Nature Reserve in the Caspian Sea. These conditions include sunshine duration, the inclination angle of the optimally oriented receiver surface, the hour angle of solar declination, direct and diffuse radiation, albedo, and average monthly and annual outdoor air temperatures. The energy parameters and operating time of a SPP with an area of 10.4 m^2, oriented at an average annual optimal inclination angle of 39°, were analyzed. Calculations indicate an average annual electricity generation of 10.03 kW·h/day, a total annual electricity generation of 3658.34 kW·h, organic fuel savings of 1463.336 kg per year, and reductions in harmful emissions as follows: SO_2 – 30.41 kg/year; NO_x – 16.38 kg/year; CO – 2.13 kg/year; CH_4 – 4.47 kg/year; CO_2 – 2339.64 kg/year; solid substances – 3.19 kg/year.

The cost of an SPP with an energy output of 10 kW·h/day is $12,673.9. The average daily energy consumption of the laboratory premises, when operating essential electrical appliances, is 10.03 kW·h/day, with a cost of $0.055 per kW·h, excluding transportation costs via the Caspian Sea. Preliminary calculations indicate that the payback period for the photovoltaic SPP is 5 years and 6 months, with a profitability of 6.76% and a net profit of $2,234.01 over 10 years.

The findings confirm that utilizing solar and wind energy resources is a prioritized, promising, environmentally sustainable, and economically viable solution for electricity supply, energy security, and other applications along the Caspian Sea.

The results obtained from regression equations (1)–(16) will be valuable for preparing design and cost estimation documentation, as well as FS, to support the implementation of solar and wind energy technologies in the region.

The implementation of these technologies will address various energy supply challenges at the Khazar Nature Reserve on Ogurchinsky Island. The adoption of modern electronic technologies will enhance the reliability of data obtained from flora and fauna observations, support the conservation of biological resources and biodiversity, improve social and living conditions for workers and residents, and reduce the anthropogenic impact on the ecosystem. These efforts will contribute to Turkmenistan's National and State Energy, Socio-Economic and Environmental Sustainable Development Programs, as well as the Paris Agreement on Climate Change, the outcomes of the 28th session of the Conference of the Parties to the UN Framework Convention on Climate Change (COP28), and other national and international initiatives.

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About the authors:

Ahmet M. Penjiyev, Associate Professor, Turkmen State Institute of Architecture and Civil Engineering (1 B. Annanova Str., Ashgabat, 744001, Turkmenistan), DSc (Tech.), DSc (Agric.), *ampenjiyev@gmail.com*

Batyr M. Mamedov, Rector, Turkmen State Institute of Architecture and Civil Engineering (1 B. Annanova Str., Ashgabat, 744001, Turkmenistan), DSc (Tech.), DSc (Agric.), *tdbgi@online.tm*

Contribution of the authors:

Ahmet M. Penjiyev – basic concept statement, scientific supervision, statement of study goals and objectives, calculations, text preparation, revision of literary analysis, text editing

Batyr M. Mamedov – analysis and discussion of the study results, formulation and editing of conclusions

All the authors have read and approved the final manuscript.