

SOLAR-ENERGY POTENTIAL OF OPTIMALLY ORIENTED AREAS OF THE WRINKLED TERRAIN ON THE NORTHERN COASTAL ZONE OF THE MINGECHEVIR RESERVOIR

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Summary. This study evaluates the solar-energy potential of naturally inclined terrain along a 200 m-wide landward strip of the wrinkled northern coast of the Mingachevir Reservoir, Azerbaijan. The study line extends from map-derived point A (41.0028° N, 46.6509° E) to point B (40.8000° N, 47.1127° E). The methodology combines the “time-of-use” optimal-orientation approach of Gardashov (2022), terrain slope and aspect screening, and long-term solar-resource information from the Global Solar Atlas, ERA5 and MERRA-2. To prevent positional uncertainty from including reservoir water or deep inland terrain, the endpoints are treated as along-shore anchors, the shoreline is traced between their nearest coastal positions, and a one-sided 200 m landward buffer defines the study polygon. Annual, spring/summer and autumn/winter target orientations were taken as 34°/180°, 19°/180°, and 56°/180° (tilt/azimuth), respectively, with stated angular tolerances. In the numerical terrain model, the georeferenced shoreline and the Copernicus GLO-30 DEM tiles were used. The screening indicates that the north shore is structurally favourable because many slopes face generally south towards the reservoir. The estimated suitable terrain area is largest for summer and spring-autumn orientations, smaller for the annual orientation, and limited for the steep winter orientation. The results support the concept of using naturally oriented coastal slopes for PV placement, while demonstrating that final engineering quantities require direct high resolution DEM, land-cover, geotechnical and grid-access data.

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1. Introduction

Mingachevir Reservoir is located on the Kura River in central-western Azerbaijan and was created as part of the Soviet-era hydroelectric and water-management development of the region. The reservoir and its dam-hydroelectric complex supported the establishment and growth of the modern city of Mingachevir. A total engineered capacity is approximately 16 billion m³ and there is a relationship between the reservoir, the dam and the city that developed around the power project (NASA Earth Observatory, 2010).

The reservoir remains economically important for hydropower, water regulation, irrigation, fisheries, recreation and regional development. Mingachevir is widely regarded as one of Azerbaijan’s principal energy centres; official information indicates that a large share of the country’s electricity generation is concentrated in Mingachevir, reflecting both its hydropower legacy and its later thermal-power infrastructure (President of the Republic of Azerbaijan, 2025). The reservoir is also Azerbaijan’s largest and supports boating, fishing, tourism and biodiversity-related activities (Azerbaijan Tourism Board, 2026).

The northern coastal zone shown in Fig 1 consists of elongated, eroded hills and slopes that descend generally southwards towards the reservoir. This geometry is potentially favourable for fixed photovoltaic

installations because south-facing terrain can naturally approximate the azimuth and tilt of an optimally oriented PV panel. The current study aims to identify shares of the terrain whose slope and aspect fall within prescribed neighborhoods of annual or seasonal optimum panel orientations and to estimate their solar-resource characteristics.

The present work extends the “time-of-use” orientation concept proposed by Gardashov (2022) which is based on the research of Gardashov et al. (2000). In that approach, daily optimal tilt and incident direct solar energy are combined using energy weights to obtain the optimal orientation for any selected time interval. Here, the same concept is applied to the terrain itself: a DEM cell is considered naturally suitable when its tilt and azimuth are sufficiently close to the target PV orientation for the selected period.



Fig. 1. Google Earth view of the Mingechevir Reservoir and the map-derived northern-shore study line from A to B.

2. Description of the study area and data sources

The adopted endpoints are A = 41.0028° N, 46.6509° E and B = 40.8000° N, 47.1127° E. Their uncertainty is accepted only along the shoreline. Cross-shore uncertainty is removed by snapping the points to the northern water-land boundary and constructing a one-sided buffer extending 200 m landward. The preliminary traced shoreline length is approximately 45.3 km, giving a nominal corridor (coastal zone) area of about 9.07 km² before exclusions.

The Global Solar Atlas reports Azerbaijan-wide long-term ranges of approximately 3.44–4.80 kWh m⁻² day⁻¹ for GHI, 3.82 – 5.56 kWh m⁻² day⁻¹ for optimum-tilt irradiation and 29–37° for optimum annual tilt (World Bank/ESMAP and Solargis, 2026). The annual target tilt of 34° adopted here lies within that range. ERA5 and MERRA-2 are included in the final workflow to calculate monthly means, variability, minima and maxima, and to cross-check the atlas climatology (Gelaro et al., 2017; Hersbach et al., 2020). The information about data sources and their role in the current study is given in Table 1.

Table 1

Data sources and their role in the analysis

Source	Role	Important qualification
Supplied Google Earth map	A-B endpoints and visual shoreline geometry	Map-derived; approximate
Copernicus DEM GLO-30	Elevation, slope and aspect for final GIS model	30 m DSM; final recommended source
Global Solar Atlas	Long-term GHI, DNI, GTI and optimum tilt	1994/1999/2007-2018 climatology, source dependent
ERA5	Hourly surface solar radiation and meteorology	1940-present; reanalysis
MERRA-2	Hourly solar and atmospheric fields	1980-present; independent reanalysis
Gardashov (2022)	Energy-weighted “time-of-use” optimal orientation	Published mathematical/software method

3. Methodology

Shoreline-constrained terrain corridor

The shoreline is treated as the water-land boundary. The A-B shoreline segment is selected and a 200 m one-sided landward buffer is formed. Reservoir-water cells are excluded by the water mask, and all terrain beyond 200 m inland is removed. This procedure implements the clarification that endpoint uncertainty may act along the coastal line but must not place the study area in water or deep inland terrain.

Terrain tilt and azimuth

For a georeferenced elevation surface $z(x, y)$, the local gradients $\partial z/\partial x$ and $\partial z/\partial y$ are calculated.

Terrain tilt θ and downslope azimuth φ are obtained from

$\theta = \arctan \sqrt{(\partial z/\partial x)^2 + (\partial z/\partial y)^2}$ and the four-quadrant aspect relation. Flat or unreliable water-mask cells are omitted. Copernicus GLO-30 is used because it provides open 30 m elevation data; it is technically a digital surface model and therefore may include vegetation and structures (Copernicus Programme, 2024).

“Time-of-use” optimal orientation

Gardashov (2022) defines the optimal tilt, $\theta_{opt_time\ of\ use}$, for a selected time interval (“time-of-use”) by weighting daily optimal tilts θ_{opt_i} , ($i = 1, 2, \dots, 365$) with the corresponding incident direct solar energy S_i :

$$\theta_{opt_time\ of\ use} = \sum_{i=i_1}^{i_2} \theta_{opt_i} \cdot p_i, \quad p_i = S_i / \sum_{j=i_1}^{i_2} S_j$$

Where, i_1 and i_2 the day numbers of year between which optimal direction of panel for “time of use” should be found.

The same principle can be applied to azimuth through a circular energy-weighted mean. In Table 2 for the present calculation, the adopted south-facing target orientations and tolerances are listed.

Table 2

Target PV orientations and screening tolerances

Period	Target tilt (°)	Target azimuth (°)	Tilt tolerance, $\Delta\theta$	Azimuth tolerance, $\Delta\varphi$
Annual	34	180	$\pm 6^\circ$	$\pm 20^\circ$
Spring	19	180	$\pm 6^\circ$	$\pm 20^\circ$
Summer	19	180	$\pm 6^\circ$	$\pm 20^\circ$
Autumn	56	180	$\pm 6^\circ$	$\pm 20^\circ$
Winter	56	180	$\pm 6^\circ$	$\pm 20^\circ$

A terrain cell is classified as suitable when $|\theta - \theta_{opt}| \leq |\Delta\theta|$ and the circular azimuth difference $|\varphi - \varphi_{opt}| \leq |\Delta\varphi|$. Adjacent suitable cells are grouped into numbered regions. The area of the suitable region equals to the number of selected cells multiplied by the projected cell area.

Solar irradiation on selected relief

The final calculation uses hourly direct normal irradiation (DNI), diffuse horizontal irradiation and global horizontal irradiation, followed by a transposition model for each cell’s tilt and azimuth. The beam component is obtained from DNI multiplied by the cosine of the incidence angle; diffuse and ground-reflected terms can be estimated with an isotropic, Hay-Davies or Perez model (Duffie & Beckman, 2013; Perez et al., 1990). Monthly and annual energy are summed over time. ERA5 and MERRA-2 provide independent long-term atmospheric forcing, whereas the Global Solar Atlas provides a high-resolution long-term benchmark.

For the preliminary numerical tables, an annual horizontal resource of approximately

$1585 \text{ kWh m}^{-2} \text{ yr}^{-1}$ and an annual optimum-plane resource of approximately $1875 \text{ kWh m}^{-2} \text{ yr}^{-1}$ were adopted, consistent with the central part of the Azerbaijan-wide Global Solar Atlas ranges. Seasonal values were distributed using a representative monthly climatology. These values are assumptions and they are replaced by the extracted site-specific grids in the final version.

4. Results and discussion

Fig 2(a) presents the 3D terrain model of the 200m wide A-B landward corridor (coastal zone). In Fig. 2(b), the annual suitable areas indicated as 1 and 2, are shown. Fig. 2(c) presents these same areas 1 and 2 in geographical coordinates (latitude, longitude). Fig 3 and Fig 4 present the suitable areas for Autumn/Winter and Spring/Summer periods, respectively. Fig 5 represents monthly irradiation distribution. In Table 3 the annual suitable regions and their estimated areas are given. In Table 4 the Autumn/Winter and in Table 5 Spring/Summer -suitable regions and their estimated areas are presented. In Table 6, the solar energy resource indicators for the optimal orientation periods (annual, spring/summer, autumn/winter) are presented.

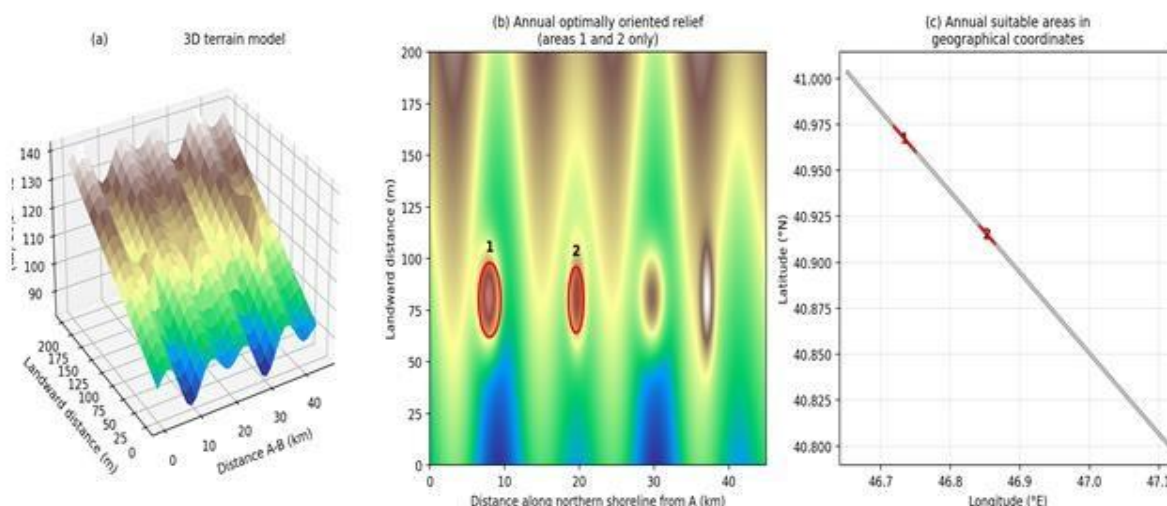


Fig. 2. (a) 3D model of the A-B landward corridor; (b) annual suitable areas 1 and 2; (c) annual suitable areas 1 and 2 presented in geographical coordinates (lat, lon).

Table 3

Annual suitable regions

Region No.	Start from A (km)	End from A (km)	Area (m ²)
1	6.56	9.49	56,293
2	18.56	20.59	34,194

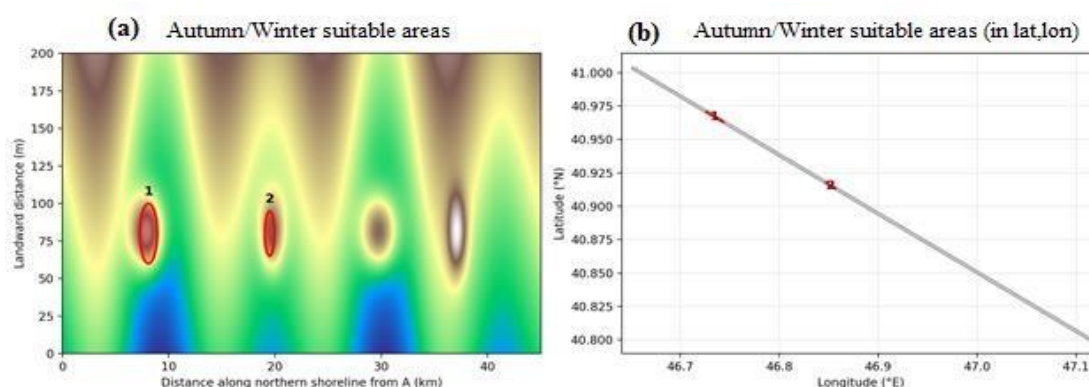


Fig 3. (a) Autumn/Winter suitable areas 1 and 2; (b) Autumn/Winter suitable areas 1 and 2 presented in geographical coordinates (lat, lon).

Table 4

Autumn/Winter -suitable regions

Region No.	Start from A (km)	End from A (km)	Area (m ²)
1	7.29	8.93	35,823
2	19.05	19.96	14,655

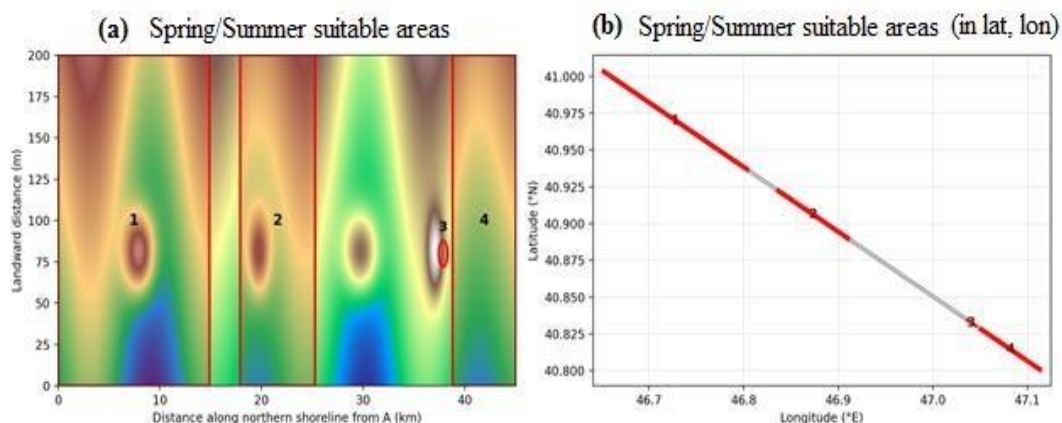


Fig 4. (a) Spring/Summer suitable areas 1, 2, 3 and 4; (b) Spring/Summer suitable areas 1, 2, 3 and 4 presented in geographical coordinates (lat, lon).

Table 5

Spring/Summer -suitable regions

Region No.	Start from A (km)	End from A (km)	Area (m ²)
1	0.00	14.90	2,804,408
2	17.93	25.26	1,276,127
3	37.44	38.31	6,513
4	38.80	45.01	1,221,462

Table 6

Areas and solar-resource indicators for the annual and seasonal optimal orientation periods

Period	Target tilt (deg)	Target azimuth (deg)	Area (m ²)	Mean energy (kWh m ⁻² period ⁻¹)	Mean irradiance (W m ⁻²)
Annual	34	180	90487	1875	214
Spring/Summer	19	180	5308510	659	305
Autumn/Winter	56	180	50477	422	195

As can be seen from Table 6, the optimal tilted area for spring/summer is approximately 50 times larger than the annual optimal tilted area and 100 times larger than the optimal tilted area for autumn/winter. At the same time, for autumn/winter period, the annual and autumn/winter optimally tilted areas receive approximately the same amount of irradiation; for summer period the annual and summer/spring optimally tilted (Fig. 5). As a result of information presented in Table 6 and in Fig 5, we obtain final assessment of solar energy potentially available for production (Table 7). The yearly produced solar energy is greater in summer/spring tilted areas and it is about 1.4 mil. MWh. This is enough to meet the electricity demands of approximately 226,000 businesses (residential buildings, infrastructure facilities, etc.) with a monthly consumption of 500 kWh. The Mingchevir Reservoir and its coastal zone are intensively used to support sport boating, fishing, tourism, and ecology-related activities, and therefore the use of clean energy is extremely important in that region.

The principal physical advantage of the northern shore is its generally south-facing downslope direction. Unlike a flat site, where mounting structures must create the complete tilt, naturally inclined terrain can reduce earthworks and support rows that follow the relief. However, favorable slope and aspect alone do not establish constructability. Geotechnical stability, erosion, drainage, access roads, vegetation, land ownership, protected zones, reservoir-level variation and grid distance must also be assessed.

The estimated areas depend strongly on angular tolerance. Narrower tolerances increase optical similarity to the ideal PV plane but reduce usable land and may fragment the selected regions. Wider tolerances increase area but can introduce shading, row-layout and non-uniformity problems. A final multi-criteria model should therefore optimize energy, grading cost, cable length, erosion risk and ecological constraints simultaneously.

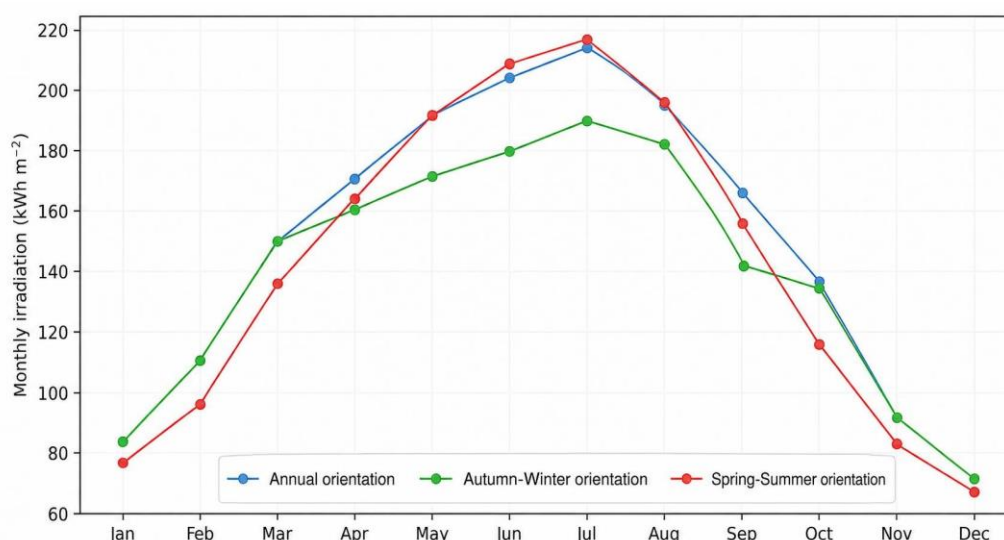


Fig 5. Monthly irradiation for optimally oriented areas in annual, autumn/winter, and spring/summer

Table 7

The Annual, Spring/Summer and Autumn/Winter optimal oriented areas solar energy indicators

Month	Annual GTI opt (kWh m ⁻²)	Annual GTI opt to Area (MWh)	Annual PV out, 15% eff (MWh)	Spring/Summer GTI opt (kWh·m ⁻²)	Spring/Summer GTI opt to Area (MWh)	Spring/Summer PV out, 15% eff (MWh)	Autumn/Winter GTI opt (kWh·m ⁻²)	Autumn/Winter GTI opt to Area (MWh)	Autumn/Winter PV out, 15% eff (MWh)
Jan	84	7600	1140	77	408755	61313	84	4240	636
Feb	111	10044	1506	96	509616	76442	111	5602	840
Mar	150	13573	2035	136	721957	108293	150	7571	1135
Apr	171	15473	2320	164	870595	130589	161	8126	1218
May	192	17373	2605	192	1.019E+06	152850	172	8682	1302
Jun	204	18459	2768	209	1.109E+06	166350	180	9085	1362
Jul	214	19364	2904	217	1.152E+06	172800	190	9590	1438
Aug	195	17644	2646	196	1.04E+06	156000	182	9186	1377
Sep	166	15020	2253	156	828127	124219	142	7167	1075
Oct	137	12396	1859	116	615787	92368	135	6814	1022
Nov	92	8324	1248	83	440606	66090	92	4643	696
Dec	72	6515	977	67	355670	53350	72	3634	545
Yearly		161785	24261		9071113	1360666		84340	12651

The method has practical relevance beyond a conventional ground-mounted PV plant. Suitable natural slopes could host distributed arrays, agrivoltaic strips, reservoir-side auxiliary power, irrigation/pumping systems, tourism facilities or hybrid land-floating PV schemes. The reservoir environment also creates possible cooling advantages, but humidity, corrosion and shoreline winds must be considered.

5. Conclusion

In the current study, the northern Mingechvir Reservoir shoreline between the map-derived A and B points is studied as a one-sided 200 m landward coastal zone without allowing coordinate uncertainty to extend into the water or deep inland. The time-of-use method of Gardashov (2022) has been adopted for the study of the annual, spring/summer, and autumn/winter optimally oriented areas of wrinkled terrain on the northern coastal zone of Mingechvir Reservoir. Future work should include high-resolution DEM validation, horizon/shadow analysis, hourly transposition modelling, PV row layout optimization, geotechnical and environmental screening, grid-connection analysis, and comparison with floating PV on the reservoir.

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ПОТЕНЦИАЛ СОЛНЕЧНОЙ ЭНЕРГЕТИКИ НА УЧАСТКАХ ХОЛМИСТОГО РЕЛЬЕФА С ОПТИМАЛЬНОЙ ОРИЕНТАЦИЕЙ СКЛОНОВ В СЕВЕРНОЙ ПРИБРЕЖНОЙ ЗОНЕ МИНГЯЧЕВИРСКОГО ВОДОХРАНИЛИЩА

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Резюме. В исследовании оценивается потенциал солнечной энергии на участках местности с естественным уклоном в пределах полосы суши шириной 200 м вдоль изрезанного северного побережья Мингячевирского водохранилища в Азербайджане. Линия исследования простирается между определёнными по картографическим данным точками А (41,0028° с. ш., 46,6509° в. д.) и В (40,8000° с. ш., 47,1127° в. д.). Методология объединяет предложенный Гардашовым (2022) подход к оптимальной ориентации с учётом времени использования солнечной энергии, оценку пригодности территории по крутизне и экспозиции склонов, а также многолетние данные о солнечных энергетических ресурсах из Global Solar Atlas, ERA5 и MERRA-2. Для предотвращения включения акватории водохранилища или удалённых от берега участков суши вследствие позиционной неопределённости начальная и конечная точки рассматриваются как опорные ориентиры вдоль побережья. Между ближайшими к ним береговыми позициями прослеживается береговая линия, после чего формируется односторонняя буферная зона шириной 200 м в направлении суши, определяющая границы исследуемого полигона. Целевые параметры ориентации для годового, весенне-летнего и осенне-зимнего периодов приняты соответственно равными 34°/180°, 19°/180° и 56°/180° (угол наклона/азимут) с учётом установленных допустимых угловых отклонений. При построении численной модели рельефа использовались геопривязанная береговая линия и соответствующие фрагменты цифровой модели рельефа Copernicus GLO-30. Оценка пригодности территории показывает, что северное побережье обладает благоприятными структурными

характеристиками, поскольку значительная часть склонов ориентирована преимущественно на юг, в сторону водохранилища. Расчётная площадь пригодных участков оказалась наибольшей для летнего и весенне-осеннего вариантов ориентации, меньшей для годового варианта и ограниченной для зимнего варианта, требующего более крутого угла наклона. Полученные результаты подтверждают перспективность размещения фотоэлектрических (PV) панелей на прибрежных склонах с естественно благоприятной ориентацией. Вместе с тем показано, что для окончательного определения инженерно-технических параметров необходимы непосредственные данные цифровой модели рельефа высокого пространственного разрешения, а также сведения о земельном покрове, геотехнических условиях и возможностях подключения к электрическим сетям.

Ключевые слова: Мингячевирское водохранилище, солнечная энергия, ориентация фотоэлектрических установок, экспозиция склонов, цифровая модель рельефа, Global Solar Atlas, ERA5, MERRA-2, время использования

MİNGƏÇEVİR SU ANBARININ ŞİMAL SAHİL ZONASINDA PARÇALANMIŞ RELYEFİN OPTİMAL SƏMTLƏNMİŞ SAHƏLƏRİNİN GÜNƏŞ ENERJİSİ POTENSİYALI

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Xülasə. Tədqiqatda Azərbaycanın Mingəçevir su anbarının girintili-çıxıntılı şimal sahili boyunca qurunun içərisinə doğru uzanan 200 m enində zolaqda təbii meyilliyə malik ərazilərin günəş enerjisi potensialı qiymətləndirilmişdir. Tədqiqat xətti xəritə əsasında müəyyən edilmiş A (41,0028° şm. e., 46,6509° ş. u.) və B (40,8000° şm. e., 47,1127° ş. u.) nöqtələri arasında uzanır. Metodologiya Qardaşovun (2022) gün ərzində istifadə vaxtına əsaslanan optimal istiqamətləndirmə yanaşmasını, relyefin meyilliyi və yamacların ekspozisiyası üzrə uyğunluğun qiymətləndirilməsini, həmçinin Global Solar Atlas, ERA5 və MERRA-2 məlumat bazalarının uzunmüddətli günəş enerjisi ehtiyatlarına dair göstəricilərini birləşdirir. Mövqe qeyri-müəyyənliyi nəticəsində su anbarının akvatoriyasının və ya sahildən uzaqda yerləşən quru ərazilərin tədqiqat sahəsinə daxil edilməsinin qarşısını almaq məqsədilə başlanğıc və son nöqtələr sahilboyu istinad nöqtələri kimi qəbul edilmiş, onların sahil xəttinə ən yaxın mövqeləri arasında sahil xətti müəyyənləşdirilmiş və qurunun içərisinə doğru bir tərəfli 200 m-lik bufer zona yaradılaraq tədqiqat poliqonu formalaşdırılmışdır. İllik, yaz-yay və payız-qış dövrləri üçün hədəf istiqamətləndirmə parametrləri müvafiq olaraq 34°/180°, 19°/180° və 56°/180° (meyillik bucağı/azimut) qəbul edilmiş və bucaqlar üzrə yol verilən kənarlaşmalar nəzərə alınmışdır. Relyefin rəqəmsal modelində coğrafi koordinatlarla əlaqələndirilmiş sahil xəttindən və Copernicus GLO-30 rəqəmsal yüksəklik modelinin müvafiq fraqmentlərindən istifadə edilmişdir. Ərazilərin uyğunluq baxımından qiymətləndirilməsi göstərir ki, şimal sahili struktur baxımından əlverişlidir, çünki yamacların əhəmiyyətli hissəsi ümumilikdə cənuba, su anbarına doğru istiqamətlənmişdir. Günəş enerjisindən istifadə üçün uyğun hesab edilən ərazilərin təxmini sahəsi yay və yaz-payız istiqamətləndirmə variantlarında ən böyük, illik istiqamətləndirmə variantında nisbətən kiçik, daha böyük meyillik bucağı tələb edən qış variantında isə məhdud olmuşdur. Nəticələr təbii istiqamətlənmiş sahil yamaclarında fotovoltaiq (PV) panellərin yerləşdirilməsi konsepsiyasının məqsədəuyğunluğunu təsdiqləyir. Bununla yanaşı, yekun mühəndis-texniki hesablamaların aparılması üçün yüksək məkan ayırdetməsinə malik birbaşa rəqəmsal yüksəklik məlumatlarının, torpaq örtüyünə, geotexniki şəraitə və elektrik şəbəkəsinə qoşulma imkanlarına dair məlumatların əldə edilməsinin zəruriliyi göstərilir.

Açar sözlər: Mingəçevir su anbarı, günəş enerjisi, fotoelektrik qurğuların səmtlənməsi, yamacların ekspozisiyası, rəqəmsal yüksəklik modeli, Global Solar Atlas, ERA5, MERRA-2, istifadə vaxtı