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OPTIMAL SITE SELECTION FOR THE INSTALLATION OF SOLAR PV PLANTS: A CASE STUDY IN NAKHCHIVAN AR, AZERBAIJAN

Since the electrical power produced by converting total solar radiation on horizontal surface, composed of direct and diffuse components of PV cells, has low output power, it is necessary to identify areas with high power factor for more efficient power generation. However, due to the low efficiency of PV panels (14-18%) and the low intensity of total solar radiation on horizontal surface, large installation space is required to achieve a certain power level. Due to the high cost of installing solar power plants, a comprehensive systematic assessment of the geographic factors of the region is required to select the most suitable location. The reason we chose Nakhchivan as the study area is that the radiation level is high compared to other regions of Azerbaijan (1220-1699 kWh/m^2-year), and the number of hours of sunshine per year exceeds 2500. Since the creation of solar power plants in regions with high values of total radiation on a horizontal surface depends on technical, economic and environmental criteria, descriptive criteria are used to determine the optimal areas. This model was used to determine a suitable installation location for solar power plants.

As a result, the study, it was concluded that 9.5% (510 km^2) of the land of Nakhchivan have high suitability, 12% (645 km^2) – average suitability and 24% (1290 km^2) – low suitability for placing solar power plants. The remaining 54.5% (2930 km^2) of the region belongs to the territories that are not suitable for use due to low radiation, high slope, the presence of protected areas, settlements, agricultural areas and poorly developed infrastructure. Optimal locations cover mainly the southern and eastern parts of the region, as shown in the polygon shape on the suitability map.

Key words: renewable energy sources, solar energy, geographic information systems, analytical hierarchy process, site selection.

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Әзірбайжан Нахичеван АР мысалында күн фотоэлектр станцияларын орнату үшін оңтайлы аумақтарды таңдау

Фотоэлектрлік панель элементтерінің тікелей және шашыраңқы компоненттерінен тұратын көлденең бетіндегі күн радиациясын түрлендіру арқылы өндірілетін электр энергиясы төмен шығу қуатына ие болғандықтан, электр энергиясын тиімдірек өндіру үшін жоғары қуат коэффициенті бар аудандарды анықтау қажет. Алайда, ФЭ-панельдерінің тиімділігі төмен (14-18%) және көлденең бетіндегі күн радиациясының қарқындылығы төмен болғандықтан, белгілі бір қуат деңгейіне жету үшін орнату үшін үлкен орын қажет. Күн электр станцияларын орнатудың қымбаттығына байланысты ең қолайлы орынды таңдау үшін аймақтың географиялық факторларын жан-жақты жүйелі бағалау қажет. Біздің Нахичеванды зерттеу аймағы ретінде таңдағанымыздың себебі, радиация деңгейі Әзірбайжанның басқа аймақтарымен салыстырғанда жоғары (1220-1699 кВт/м^2-жыл) және жыл сайын күн сәулесінің сағат саны 2500-ден асады. Көлденең бетінде жалпы радиацияның жоғары мәндері бар аймақтарда күн электр станцияларын құру техникалық, экономикалық және экологиялық өлшемдерге байланысты болғандықтан, оңтайлы аудандарды анықтау үшін сипаттамалық критерийлер қолданылады. Бұл модель күн электр станцияларын орнатудың қолайлы орнын анықтау үшін пайдаланылды. Зерттеу нәтижесінде Нахичеван жерінің 9,5% (510 км^2) жоғары жарамдылыққа, 12% (645 км^2) орташа жарамдылыққа және 24% (1290 км^2) күн электр станцияларын орналастыруға төмен жарамдылыққа ие деген қорытынды жасалды. Қалған облыстар 54,5% (2930 км^2) радиацияның төмен болуы, еңістің жоғары болуы, қорғалатын аумақтың, елді мекендердің, ауыл шаруашылығы аумақтарының болуы және инфрақұрылымның нашар дамуы салдарынан пайдалануға жарамсыз аумақтарға жатады. Оңтайлы орындар негізінен аймақтың оңтүстік және шығыс бөліктерін қамтиды және жарамдылық картасында көпбұрыш түрінде көрсетілген.

Түйін сөздер: жаңартылатын энергия көздері, күн энергиясы, географиялық ақпараттық жүйелер, аналитикалық процестің иерархия моделі, орын таңдау.

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Выбор оптимальных территорий для установки солнечных фотоэлектрических станций: на примере Нахичеванской АР, Азербайджан

Поскольку электрическая энергия, производимая путем преобразования суммарной солнечной радиации на горизонтальной поверхности, состоящей из прямых и рассеянных компонентов элементов фотоэлектрических панелей, имеет низкую выходную мощность, необходимо определить области с высоким коэффициентом мощности для более эффективного производства электроэнергии. Однако, из-за низкого КПД ФЭ-панелей (14-18%) и низкой интенсивности суммарной солнечной радиации на горизонтальной поверхности для достижения определенного уровня мощности требуется большое пространство для установки. Из-за высокой стоимости установки солнечных электростанций для выбора наиболее подходящего места требуется комплексная систематическая оценка географических факторов региона. Причина, по которой мы выбрали Нахичевань в качестве района исследования, заключается в том, что уровень радиации высок по сравнению с другими регионами Азербайджана (1220-1699 кВтч/м^2-год), и число часов солнечного сияния в год превышает 2500. Поскольку создание солнечных электростанций в регионах с высокими значениями суммарной радиации на горизонтальной поверхности зависит от технических, экономических и экологических критериев, для определения оптимальных площадей используются описательные критерии. Данная модель была использована для определения подходящего места установки солнечных электростанций.

В результате исследования был сделан вывод, что 9,5% (510 км^2) земли Нахичевани имеют высокую пригодность, 12% (645 км^2) – среднюю пригодность и 24% (1290 км^2) – низкую пригодность для размещения солнечных электростанций. Остальные области – 54,5% (2930 км^2) относятся к территориям, которые не подходят для использования из-за низкой радиации, высокого уклона, наличия охраняемой территории, населенных пунктов, сельскохозяйственных территорий и слабо развитой инфраструктуры. Оптимальные места охватывают в основном южную и восточную части региона, и на карте пригодности показаны в форме многоугольника.

Ключевые слова: возобновляемые источники энергии, солнечная энергия, геоинформационная система, модель аналитической иерархии процесса, выбор места.

Introduction

The choice of a geographically suitable site for efficient energy production in photovoltaic solar power plants depends on many factors. To obtain a concrete result, more realistic figures can be obtained by examining the spatial and meteorological data of the region in geographic information systems (GIS) (Khan & Rathi, 2014). The number of sunny days in the Nakhchivan AR is about 250, and the average radiation level is 1460 kWh/m^2 per year, which makes this area suitable for investments in solar panels installations (Mammadov, 2013). Therefore, from the point of view of the energy security of the region, it is necessary to identify suitable sites for the use of solar energy with low cost and maximum benefit. In the study, a multi-criteria decision-making technique was used to determine the suitability of locations. This approach is the best identification method for analyzing complex and multi-format data obtained to achieve a specific goal (Wang et al., 2018). The use of spatial GIS and multi-criteria method in the form of integration can help in an in-depth analysis of natural events, rational and systematic identification and interpretation of different levels of risk (Linkov & Moberg, 2011).

The MCDM-based analytical hierarchy process (AHP) model is used to superpose the data obtained from the analysis performed in the outcome study and to identify the corresponding regions. The ultimate goal of the AHP method is to find an alternative way to achieve the overall result by analysing the collected data in terms of multiple criteria and conflicting goals (Uyan, 2013). The primary goal here is to determine the zone with medium and the high energy potential following the principles of site selection for solar power plants.

Concerning economical and efficient power generation, the planning stage of the power plant site considers the annual sunshine in the region, radiation levels, land use, agricultural efficiency, distance to roads, power lines and other constraints. At the same time, physicals object that pollutes the surface of photovoltaic panels and creates shadow effects are among the criteria that directly affect energy production (Vulkan et al., 2018).

There are many examples of the use of multi-criteria GIS-based methods to determine the most optimal locations Because each country has its unique natural environment (Beccali et al., 2003). For example, in a study to determine a suitable territory for a solar power plant in Iran, 11 criteria were taken into account (Noorollahi et al., 20160. Since the superiority of these criteria relative to each other is uncertain, a model of the analytical hierarchy of the process was used for weighing and a map of the suitability of territories for solar power plants in a GIS environment was created. A study of Saudi Arabia, which used methods of an analytical hierarchical process, concluded that the most suitable territories for solar power plants are the northern and north-western regions of the country (Al Garni & Awasthi, 2017). This method has played a decisive role in determining the optimal area by the principles of placing photovoltaic installations at a certain distance from the boundary zone, such as agricultural areas, protected natural areas, residential areas. Studies to identify a suitable area in Khuzestan province (Iran) concluded that even in the worst-case scenario, the potential for solar energy production is approximately 1.75 times the total electricity generated in Iran in 2016. Here, with the widespread use of solar power plants, installation and infrastructure costs will be amortized and the total cost of generating solar energy will decrease compared to fossil fuels (Asakereh et al., 2017). In another study, four main criteria (radiation, topography, feasibility and environmental criteria) and eight sub-criteria were identified for planned solar power plants in Eastern Morocco, and a suitability map of potential regions was created. As a result of the study, it was determined that 19% of the eastern part of Morocco is quite suitable for the installation of solar power plants (Merrouni et al., 2018).

In addition, there are several examples of assessing various alternative energy sources using a combination of different methods based on making multi-criteria decisions for assessing large areas. The ELECTRE model was applied, which includes a multi-criteria decision-making method used to evaluate an action plan for research on renewable energy technologies applies at a regional scale. For example, on the island of Sardinia (Italy), three decision-making scenarios were proposed, each of which represents an agreed sequence of actions, based on the development of strategies to uncover the advantages and disadvantages of using renewable energy sources (Beccali et al., 2003; Devi & Yadav, 2013). However, the potential of geothermal energy sources on the island of Chios (Greece) was assessed by intercom paring the PROMETHEE II and ELECTRE III methods (Polatidis et al., 2015). According to various sustainability criteria, the method MODERGIS has been proposed for planning and modelling renewable energy in Colombia (Quijano et al., 2010). With this method, the study area was first classified according to the solar energy potential, then the environmental parameters were analysed and suitable areas for large photovoltaic installations were determined.

Materials and methods

The Digital Elevation Model (DEM) data of the study area was obtained from the open-source ALOS-PALSAR satellite to calculate and map elevation, slope and radiation values in a GIS environment. In addition, climatic data from 1990 to 2018, data from the Global Solar Atlas (GSA), Solargis and the corresponding meteorological maps were used to determine the values of radiation in Nakhchivan.

In the literature, there are several studies of the AHP model included in the MCDM methodology, which is based on its integration with GIS systems when choosing a site for the construction of solar power plants. In these studies, there are various criteria that determine the choice of a suitable site. This is because when the same criteria are applied, the accuracy of the figures obtained does not reflect the truth, as work areas have their unique characteristics in terms of conditions such as topography, radiation, land use and infrastructure. Thus, in accordance with the principles of solar energy installation, the main criteria related to the relief, climatic and ecological characteristics of the territory are determined. The data collected for this purpose were grouped into 3 classes, from high to low availability. These data 1. spatial: height, slope, hill shade and aspect 2. climate: total solar radiation on the horizontal surface, air temperature, 3.

environment: land use, protected areas 4. infrastructure: roads and power lines. All data generated to create a suitable GIS location was weighted in total as 100% in the impact table using the successive function to raster, Euclidean distance, reclassification, weighted overlay tools in the model builder. In addition, the study also implies the methods of mathematical-statistical, cartographic and geographic modelling.

Three different types of data were studied, the criterion of which is a certain location, suitable for the installation of solar power plants in regions with high solar potential.

– features of the relief of the region and land use;

– meteorological characteristics, including the value of the total solar radiation on a horizontal surface;

– energy capacities and infrastructure of the district (power grids, substations, roads, etc.);

– However, there are the following basic factors to consider when planning a solar power plant installation in any area;

– current demand for electricity in the region and the dynamics of growth of this demand in the coming years;

– the potential of solar energy resources in the region and its share in the total energy demand, as well as the possibility of using it in competition with traditional energy;

– economic efficiency and environmental advantage of solar energy sources.

Although the total solar radiation on a horizontal surface, which is the primary requirement for choosing the optimal area for the construction of a solar station, is high, areas that correspond to the restrictive criteria are considered unsuitable. Such sites represent natural land-forms that are unsuitable for solar power plant construction unfavorable slopes (mountain ranges and hills), significant shading or confined spaces (canyons, hole). This group includes national borders with specific-purpose zones, coastal zones and territories along the perimeter of at least 1 km for which a special alliterate of use and protection has been established. At the same time, nature reserves (national parks, nature reserves, nature and landscapes) and cultural heritage sites (archaeological sites, historical settlements, etc.) are also among the restrictive criteria. It is usually noted that the optimal value of a set of factors does not contradict the optimal choice of other criteria. In the case of a “contradiction” between one parameter and another, the principle of “compliance with the criteria with the least damage” is to consider account (Gardashov et al., 2020). For example, in an area with high solar potential (i.e. with little or no mountain shade, less cloudiness, pollution and fog), a suitable site is identified to consider account additional infrastructure costs and possible production efficiency. The final decision on choosing the most suitable place is determined by the results of calculations made according to the specified method, taking into account the indicators of all parameters. Determination of the area for installing solar power plants mainly depends on the following. the total horizontal potential of solar energy in the region should be high;

- the generating capacity of solar power plants must be highly efficient (efficiency of PV panels) and economical;
- optimal azimuth and tilt of solar panels should be positions corresponding to the minimum shading effect;
- the most suitable place should be in the shortest distance to power lines, highways and places of electricity consumption.

In addition, as a result of an assessment of the economic feasibility of current solar power plants with a capacity of 27 MW in the region, it was determined that the difference in prices for solar energy production is about 2.5 times greater than for fossil fuels. The plant has an annual production capacity of 40.5 million kilowatt-hours, and the installed capacity utilization factor (CF = annual generated energy (kWh) / (plant capacity (W) × annual period (h)) is 17%. The facility was established with guaranteed incentives such as green tariffs (long-term contracts, guaranteed purchases, etc.) and has an incentive feature for the deployment of other facilities in Nakhchivan AR.

Choosing suitable a site to install a photovoltaic station is divided into 4 main criteria.

1) economic criterion: the solar energy tariff price, stimulating factors, the cost of land acquisition and power plant installation costs;

2) meteorology and technical criterion: sunshine, solar radiation, the efficiency of energy production by PV panels and optimal orientation, azimuth and tilt of the panels to the Sun;

3) geographical criterion: direction of the south slope, infertile soil, climatic conditions, restricted areas (nature reserve, mountains, wetland, etc.);

4) social criterion: the electricity demand of residential areas, additional workplaces and access to clean and free energy resources. The fourteen sub-

criteria listed above regarding the use of solar energy, which comprises the economic, technical, meteorological, geographical and social conditions of the region, are discussed separately. Based on the MCDM method, these criteria were evaluated using spatial data and the AHP block diagram, a set of formulas and solutions was created. In addition, the AHP model was applied to explain the problems listed in the research methodology presented in figure 1 and anal analyze the relevant criteria.

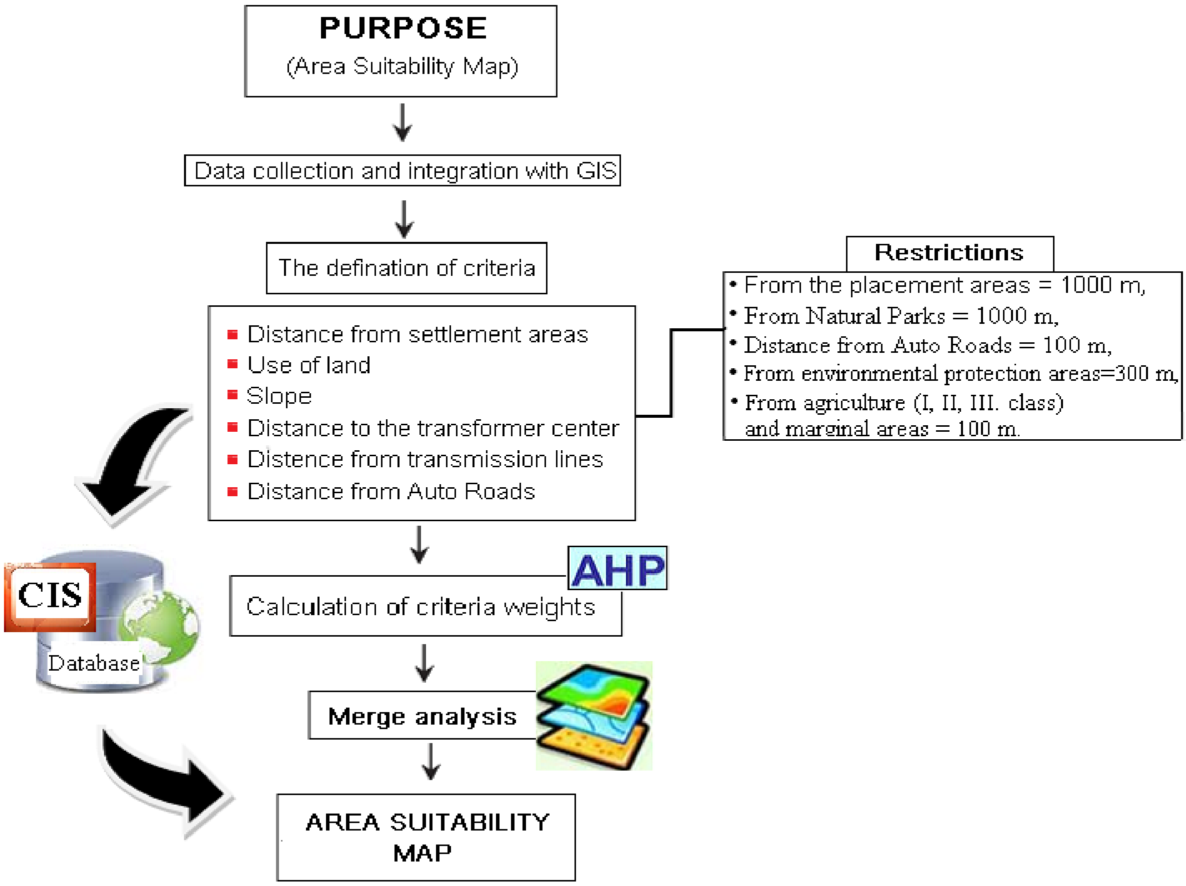

Figure 1 – General research methodology (Uyan, 2013)

In the course of the study, a pair of comparison matrices were created based on multiple comparisons between measurements, and then the weights of these criteria were made the primary criteria for determining the optimal areas. However, the consistency ratio (CR) is used to assess conflicting decisions in a pairwise comparison process. The following steps are required to fulfil the AHP for *n* criteria (Saaty, 1980).

The AHP method used in the study is one of the most comprehensive MCDM techniques to identify correct alternatives by presenting a decision coefficient for the solution of various goals. It allows the generation of a combination of qualitative and quantitative inputs that provide an optimal approach to deal with complex MCDM options in diversifying energy sources and determining the appropriate location. If the decision-maker (DM) sees an inconsistency in the results, it is possible with the AHP method was to produce a solution to explain this discrepancy. Besides, the MCDM method studies are among the most applied techniques for combining the AHP model with many selection support approaches. The AHP model has established as an accessible MCDM technique to simplify solution-result oriented investigations of such as compound decision issues (Effat, 2013; Watson, 2015). The first stage of the AHP hierarchy sets the primary aim, whereas, the middle and lower levels show selection principles and alternatives, separately. The decision-makers evaluate each standard criterion in pairwise correlations against their database. As a result, it divides the criteria into smaller sub-levels through the method and is weighted corresponding to choice-establish principles.

In the study, 4 criteria for determining the most suitable sites: solar irradiation (fig. 3), slope (fig. 5), land use, distance to roads, power lines, and settlement (fig. 6) are evaluated, and a decision matrix is formed by pairwise comparison of these criteria. The weight values of each criterion are defined through these complex equation calculations with the AHP method. A consistency ratio is then involved to eliminate contradictory decisions throughout the pairwise comparison studies. To realize the AHP method, the values of the n number of criteria are determined, and a set of formulas are applied in the following order (Saaty, 1980). To determine the consistency ratio in 6 steps with the AHP method: 1, problem definition, 2, comparison matrix creation, 3, normalization, 4, getting the priority vector, 5, consistency tests, 6, selection or ranking process is performed (fig. 2). The order of priority in the selection of suitable areas is 1. solar irradiation, 2. land use, 3. distance to roads and power lines, 4. slope.

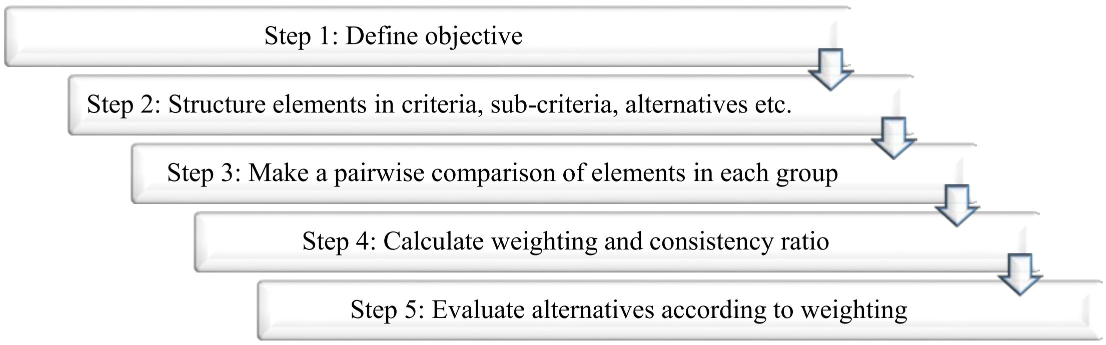

Figure 2 – Flowchart of Analytical Hierarchy Process

First, the criteria are compared among themselves. The equation developed by (Saaty 1980) is used for comparisons. The preference score for criterion j of the i criterion is determined using the A_{ij} nine-integer value scales presented to create a pairwise comparison matrix with various criteria $m = (n \times n)$. A_{ij} denominates the entry in the i row and the j column of matrix m in table 1.

Table 1 – Comparison values performed in AHP and their interpretations

Numerical values (A_{ij})	Numbers (A_{ji})	Importance level	Definition
1	1	Equally important	Criterion i and j are of equal importance
3	1/3	Slightly important	Criterion i is slightly more important than j
5	1/5	Important	Criterion i is moderately more important than j
7	1/7	Very important	Criterion i is strongly more important than j
9	1/9	Highly important	Criterion i is extremely more important than j
2,4,6,8	1/2,1/4, 1/6	Intermediate values	

The entries of preference score A_{ij} and A_{ji} must supply the following constraint in equation (1): The comparison matrix is a $n \times n$ square matrix. The matrix components on the diagonal of this matrix take the value 1.

$$\text{(Pairwise comparison matrix) } A_n \times n = a_{ij} \; A = \begin{bmatrix} 1 & A_1 & A_2 & A_3 & \cdots & A_n \\ A_1 & 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ A_2 & a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ A_3 & a_{31} & a_{31} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_n & a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} \quad (1)$$

Where, $a_{ij} = \frac{1}{Aji} (i, j = 1,2,3 \dots, n)$, total $\frac{n(n-1)}{2}$ comparisons are made. Here, for $n = 4, \frac{4(4-1)}{2} = 6$.

Then, the sum of each column requirement equals 1 to create a normalized pairwise comparison matrix $\overline{m}$. This can be obtained using equation (2) to calculate $\bar{A}_{ij}$ for each entry of matrix, $\overline{m}$ in table 2.

$$\text{(Normalization matrix equation)}, \overline{(A_{ij}} = \frac{A_{ij}}{\sum_{i=1}^{n} A_{ij}}) \quad (2)$$

Table 2 – Comparison matrix of the accepted decision criteria

	Criteria	Solar irradiation (A)	Land use (B)	Distance to roads and power lines (C)	Slope (D)
$A =$	Solar irradiation (A)	1	7	5	1/4
	Land use (B)	1/7	1	1/2	1/7
	Distance to roads and power line (C)	1/5	2	1	1/9
	Slope (D)	4	7	9	1
	Total	5.34	17	15.5	1.50

In the third step, the average values between rows are obtained to determine the relevant weights using a set of formulas (3). The relative weight for each criterion is in the range 0-1. Moreover, because of examining the criterion weight values, it appears that the direct normal irradiation factor has a greater effect on the solar PV plant area. The priority vector is obtained as follows (table 3).

$$\text{(Priority vector equation) } W_i = \frac{\sum_{i=1}^{n} A_{ij}}{\bar{n}} \quad (3)$$

Table 3 – Normalization matrix ($A_{ij} = \frac{row}{sum\ of\ rows}$)

Criteria	A	B	C	D	Normalized priority vector (W_j)	Final weights, %
A	0.187	0.412	0.323	0/166	$\sum \frac{A_{ij}}{4} = 0.272$	28%
B	0.027	0.059	0.032	0.095	$\sum \frac{A_{ij}}{4} = 0.053$	5%
C	0.037	0.118	0.065	0.074	$\sum \frac{A_{ij}}{4} = 0.073$	8%
D	0.749	0.412	0.581	0.665	$\sum \frac{A_{ij}}{4} = 0.584$	59%

In the fourth step, to obtain the solar PV suitability map (SM) is applied for each criterion of the layers formed within the scope of the study area in equation 4. If the constraint (r) comes out, $r = 0$ and this reflected on the suitability map value of an inadequate location. Otherwise, the suitability map can be obtained by finding the sum of each criterion value (x_i) multiplied by the criterion weight (w_i) (table 4).

$$SM = \sum_{i=1}^{n} x_i . w_i . r, \text{ here, } r =\in \{0,1\} \quad (4)$$

Table 4 – Weight and priority vector according to criteria

	Weight	*Priority*	*Criteria*
$W =$	0,272	2	A
	0,053	4	B
	0,073	3	C
	0,601	1	D

In the fifth step, the following formula is used to calculate the CR of the obtained values (equation 5). The consistency ratio is obtained by dividing the consistency index (CI) into the random index (RI). Here RI is the random consistency index that changes according to the number of criteria. Since the number of criteria in the study is 4, the random index equal to this value corresponds to 0.90. To determine the consistency index value of the basic criteria, the maximum eigenvalue of the comparison matrix, lambda max (λ_{max}) is found (table 5).

$$CR = \frac{CI}{RI}, \text{ here } CI = \frac{\lambda_{max} - n}{n-1} \text{ and } Aw = \lambda_{max}\, w;$$
$$CI = \frac{4.234-4}{4-1} = 0.078, CR = \frac{0.078}{0.90} = 0.086\%. \quad (5)$$

Table 5 – Determining the mean value of lambda max

$A \times w$	$\frac{Aw}{w}$	*Mean* λ_{max}
1.162	$\frac{1.162}{0.272} = 4.271$	4.234
0.215	$\frac{0.215}{0.053} = 4.035$	
0.301	$\frac{0.301}{0.073} = 4.102$	
2.722	$\frac{2.722}{0.601} = 4.525$	

The weights of the criteria presented in the site suitability studies, a binary comparison matrix was created as shown in Table 3, an eigenvector was calculated showing the priority weight of each criterion, and the sum of all weights was equal to one. CR was calculated to check the weighted values of each criterion (CR = 0.086). Since it is less than 0.10, value decisions are considered acceptable. At the same time, it is possible to evaluate the alternatives that arise when the criteria values added with sensitivity analysis using the main network tool in the "Super Decisions 3.2" application varies between 0.1-1 depending on the purpose. Four regions with high values of solar radiation for the installation of solar power plants throughout Nakhchivan using the AHP method: Sharur, Babek, Julfa and Ordubad, were evaluated as alternatives to each other. In selecting suitable sites for solar power plants, the main criteria, ranging from high to low importance level, are weighted according to the total horizontal irradiation, land use, slope and distance to roads and power lines. Subsequently, Babek district with the calculation of the matrix of pairwise comparison of data sub-criteria, such as radiation on a horizontal surface (1400-1699 kWh/m^2), land use (fertile soils, barren lands), slope (1-4°) and distance (from 1000 to 5000 meters) was identified as the most suitable location.

The selection of the location of PV panels when using the weighted overlap tool in GIS, the considered criteria (derived from the AHP model) in combination with their respective weights were considered in 3 steps;

– since the input layers have different values and ranges, each criterion must be scaled up so that it can be integrated into one layer. The values in the input maps were then classified into a general preference scale ranging from 1 to 10 (10 being the most appropriate);

– each criterion level is multiplied by the weight or significance of the criterion concerning the AHP;

– the resulting cell values are added to each other to form the final composite layer, and suitable areas were identified.

For this, a database was created in the application "ArcGIS 10.8", which has a wide range of spatial analysis tools, and the data on the total solar radiation on the horizontal surface in the region were analyzed and systematized. Then, using the proposed MCDM methodology in areas with solar potential, the best areas are determined by choosing a buffer distance between highways, power lines, agricultural land, settlements and other criteria. Finally, the most important research findings were discussed and a suitability map for photovoltaic systems was presented. In addition, this application also works in harmony with solar design and simulation programs (Homer Pro, pvPlanner, PVsyst, Solargis and others).

Results and discussion

The Nakhchivan AR is located in the south-west of Azerbaijan, at 38° 82'-39° 78' north latitude and 44° 77'-46° 13' east longitude. 65% of the territory is located at an altitude of over 750 m above sea level. The area is located in a semi-arid climatic zone. The Nakhchivan AR is surrounded by the Daralagez ridge of the Lesser Caucasus in the north, and the Zangezur ridge in the east. The area of the autonomous republic is 5387.19 km^2. The total solar radiation on the horizontal surface in the region ranges from 1220 to 1699 kWh/m^2 per year (GSA, 2020) (fig. 3). This is the highest figure in the South Caucasus with an average annual value of 1460 kWh/m^2. In addition, according to its geographic location, blockade situation and power supply security, Nakhchivan can be considered the most reasonable and most promising geographic region in Azerbaijan for solar energy investment.

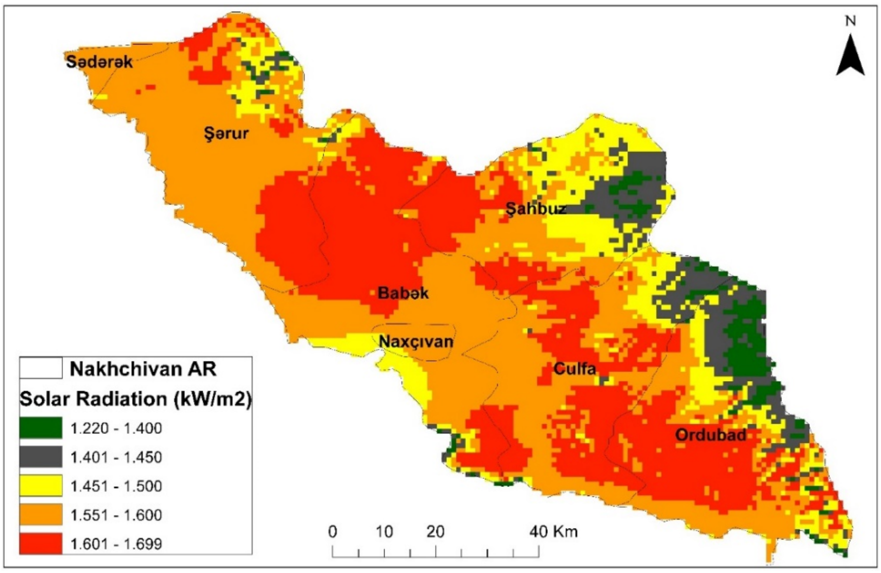

Figure 3 – Long-term average (1999-2018) of annual total GHI of Nakhchivan AR (GSA; Solargis, 2020)

The values of the total solar radiation on the horizontal surface in Nakhchivan were calculated by converting the DEM data using a solar radiation tool based on GIS and comparing the data from the GSA. Depending on topographic features, direct solar radiation values play an important role in determining the inclination and azimuth of photovoltaic panels. Since the northern parts of the autonomous republic have a medium-altitude mountainous relief, lower radiation values are observed in comparison with the southern regions. This, the angle and direction of the sun's rays play an important role in determining the installation angle of photovoltaic panels. For example, in the region, 39°21' north latitude, 45°40' south longitude, the maximum angle of the azimuth of the daylight during the year is 74.5° (June 22), and the minimum is 27.5° (December 22). The total annual sunshine duration is 2366 hours, daily sunshine duration is a maximum of 13 hours and a minimum of 8.5 hours per day. It is more convenient to install photovoltaic panels along the southern azimuth angle (between 136.78°-226.37°) at an angle of 36°-38° degrees relative to the latitude at which Nakhichevan is located (Table 5) (fig. 4). In addition, at this geographic location, the annual total horizontal DNI of 199 kWh/m², DHI of 67 kWh/m², the clarity index of 0.597 and the monthly air temperature level are close to the ideal operating range for solar panels in most months (25 °C) (table 6).

Table 6 – Average values of solar radiation, clearness index and air temperature in Nakhchivan (Solargis; GSA, 2020)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Year
Direct solar radiation on a horizontal surface (kWh/m²)	92	132	180	226	271	307	306	283	235	163	107	83	199
Diffuse solar radiation on a horizontal surface (kWh/m²)	35	52	77	90	97	96	99	79	61	52	40	30	67
Clearness Index (K_t)	0.502	0.536	0.557	0.559	0.588	0.634	0.647	0.661	0.660	0.594	0.533	0.504	0.597
Temperature (C)	-4.6	-0.3	5.9	10.6	15.3	20.3	24.0	24.4	19.3	13.2	5.4	-0.6	11.1

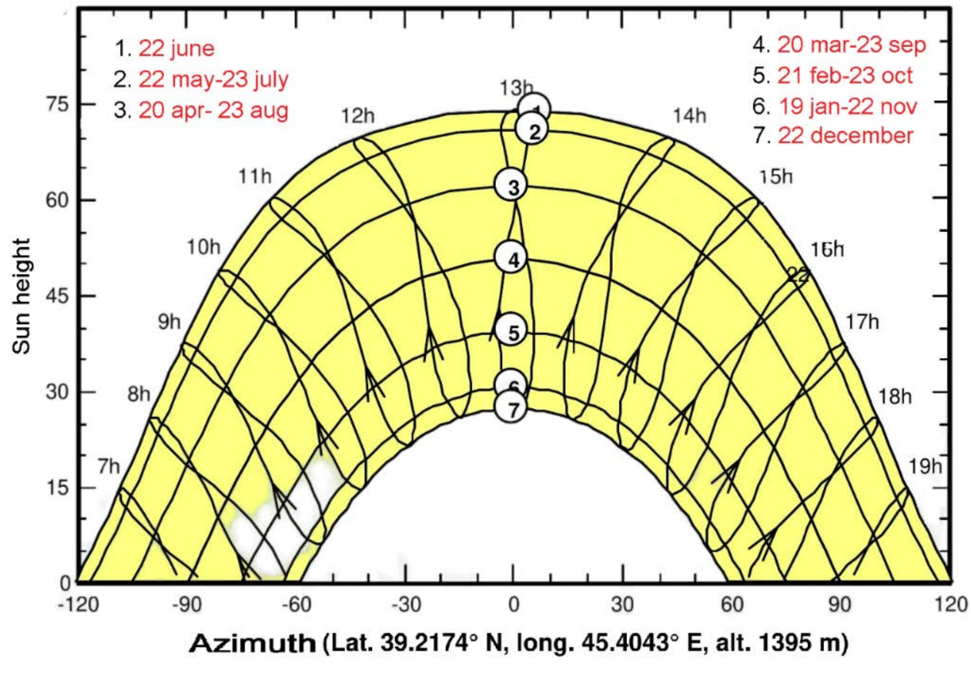

Figure 4 – The angle of incidence of the sun's rays and sunshine duration in Nakhchivan

The spatial data included in the study were obtained from advanced land observation system (ALOS), progressive array synthetic aperture radar (PALSAR) and Landsat 7 satellites (Alaska Satellite Facility, 2020). The digital elevation model data has a resolution of 12.5 x 12.5 meters and elevation, slope and aspect maps were created using these data. The slopes and terrain aspects of the surfaces of the Sharur, Ordubad, Julfa, Shahbuz and Babek districts were determined using ArcMap tools. Thus, it was determined that installing photovoltaic panels on construction sites with a slope of up to 4° or 7% is more suitable in terms of energy production and principles of economic efficiency.

The annual sunshine duration, which is one of the most important parameters for the efficient operation of photovoltaic power plants in the region, is at least 2470 hours and the annual average horizontal radiation level per square meter is 1460 kWh (4.35 kWh/m² per day) (Table 7) (fig. 3). In the distribution map of annual sunshine duration in Nakhchivan, the average duration is calculated as 10.5 hours per day (Global Monitoring Laboratory, 2020). In order for solar power plants to work efficiently, areas with at least 6.5 hours of sunshine and the least cloud cover that affect the energy flow by 10-25% should be preferred (Sunpower, 2020).

Table 7 – Duration of sunshine and areas with a slope of up to 4° (7%) (Babayev, 1999)

	Districts	Area size (km^2)	Duration of sunshine, hours/year
1	Nakhchivan	92.6	2366
2	Sharur	387.8	2597
3	Julfa	287.9	2370
4	Ordubad	198.7	2559
5	Shahbuz	218.6	2592
6	Sadarak	58.4	2660
7	Babek	135.7	2475

Another important criterion for choosing an installation site is the deployment of a power plant at a minimum distance from the consumer. Thus, it is more appropriate to locate stations near sectors with a high demand for electricity, such as urban settlements, enterprises, industrial production and factories. Data such as power lines, transformers, highways, protected zones and farmland, collected from the appropriate thematic maps and the OpenStreetMap database, were evaluated to determine the optimal location for a power plant installation. In addition, land subsidence, landslides, floods and areas prone to other natural disasters should be considered in the site selection and should be within a certain range of buffer distances with optimal areas (Al Garni & Awasthi, 2017).

In the study, the measured values characterizing the sub-criteria and limitations within the major criteria for determining the most suitable areas are described in detail in table 8. Here, in terms of importance is considered following limiting factors:

– buffer distance of 500 meters to residential areas, prohibited and protected areas;
– 400 meters from lakes;
– sites with a slope of up to 7%;
– 300 meters buffer distance to rivers;
– buffer distance of 100 meters to agricultural land;
– 300 meters from highways.

At the same time, in regions where the total solar radiation on the horizontal surface, which is the main determining criterion, is below 1350 kWh/m^2 per year, was included in unsuitable areas due to the low power generation capacity. For example, with a total radiation of 1350 and 1500 kWh/m^2, the difference in energy production by solar panels on an area of 1000 m^2 will be approximately 17000 kWh/year (151783 and 168647 kWh/year, respectively). This is calculated based on the formula for calculating the solar yield of a photovoltaic system (eq.).

$$E = A \times r \times H \times PR$$

Here, E = generated electrical energy (kWh), A = total solar panel area (m^2), r = solar panel efficiency (15%), H = radiation entering the inclined receiving surface of the panels (shading not included) and PR = coefficient loss (0.75). Depending on the location, technology and size of the system, this 25% loss includes: – inverter losses (6% to 15%), – temporary losses (5% to 15%), – DC cable losses (1 to 3%), – AC cable loss (1 to 3%), –

shading loss, (0% to 40%) (depending on the area), – loss due to low radiation (3% to 7%), – losses due to dust, snow (2%) (Solar Energy Output, 2020).

Areas were identified in the region that corresponding the criteria in table 4, and the classification of their buffer distance resulted in a thematic map at a scale of 1:50000 (fig. 6) This map is created using a weighted overlay of spatial and meteorological analysis of the region using the ArcGIS reclassification tool and AHP model. The raster imaging tools, raster-based distance tools, and Euclidean distance tools were used to determine the buffer distance of the bounding regions (table 9). Installing solar power plants near residential areas provides an economic advantage in terms of lossless transmission of electricity. In addition, at least 1 km of territory around residential areas is selected as a buffer zone, taking into account future demographic changes in certain places. For residential areas, it has been marked on the map as buffer zone 1 (> 1000 m), buffer zone 2 (1001-2000 m), buffer zone 3 (2001-5000 m) and buffer zone 4 (<5000 m) (fig. 6). As a result, the area of all defined regions was calculated using the weighted overlay tool in the GIS environment using the analytical process hierarchy method.

Table 8 – Site selection criteria for solar power plants (Doorga et al., 2019)

Criteria	Sub criteria	Specifications
Solar energy potential	Total solar radiation on a horizontal surface	1350 kWh/m^2-year and above
Topography	Slope	Up to 4^0 (7%)
Climate	Duration of cloudy days	Up to 45 days
Land use	Soils unsuitable for agriculture	Barren soils (sandy soils, grey soils, gray-brown soils, soils prone to wind and water erosion)
Power supply connection	Distance to power lines	Up to 5 km
Distance to energy consumption zones	Distance to substations	Up to 10 km
	Distance to settlements	Between 300-15000 meters
Transport	Distance to the road	From 300-500 meters
Distance to protected areas	National parks and wildlife sanctuary	
Distance to protected areas	Streams, lakes, rivers, etc.	

Another criterion in identifying potential territories for the development of solar power plants is the determination of the slope and aspect of the terrain of the region in accordance with the principles of installing power plants. To do this, the raster data of the DEM was converted into a polygon format, divided into 4 parts according to the degree of slope, and the surface area was calculated for each. The obtained area values mainly cover the flat areas and the southern slopes of the region. Thus, it was concluded that the regions of the Autonomous Republic with a slope of up to 7% (4°) in the category of the most suitable place occupy an area of 1244 km^2. The installation of solar power plants in the region on a total area of 1786 km^2 with a slope of 7-21% (4°-12°) is more costly from an economic point of view due to the steepness of the slopes [Solargis, 2020]. However, by following the technical procedures, it is possible to convert the PV panels to be placed inaccessible locations. The installation of solar power plants of the third (1239 km^2) and fourth (1270 km^2) categories with a slope of 21-39% (12°-20°) and 39-100% (20°-45°) in the map, includes areas that are difficult to use solar energy (fig. 5). These data were weighted for all regions by applying a binary matrix for comparing their criteria using the method of AHP (table 4).

Table 9 – Determination of the suitability of the site according to the main criteria, sub-criteria and indicators for the installation of solar power plants

Major criteria	Sub-criteria	Indicators	Average values	Suitability status
Solar energy potential	Total solar radiation on a horizontal surface (kWh/m^2-year)	1220-1350	1285	Low suitable
		1351-1500	1420	Medium suitable
		1501-1699	1600	High suitable
Topography (relief, slope, aspect)	The tilt angle of solar panels (south direction)	1. latitude of the region (38-40° north latitude) 2. solar panels, annual fixed angle (36°, 37° and 38°)	Angle calculation, $38° \times 0,87 + 3,1 = 36°$	Suitable
			$39° \times 0,87 + 3,1 = 37°$	
			$40° \times 0,87 + 3,1 = 38°$	
	The surface slope of the region	7-21% (4°-12°)	14% (8°)	High suitable
		21-39% (12°-20°)	30% (16°)	Medium suitable
		39-100% (20^0-45^0)	60% (31°)	Unsuitable
Climate	Altitude (range of favorable climatic conditions)	750-965 m	850 m	High suitable
		965-1200 m	1080 m	Medium suitable
		≥1200 m	≥1200 m	Unsuitable
	Number of cloudy days in the area	65-75 days	70 days	Unsuitable
		55-65 days	60 days	Medium suitable
		45-55 days	50 days	High suitable
Electrical connection	Distance to power lines	≤5 km	2,5 km	High suitable
		6-10 km	8 km	Medium suitable
		≥11 km	≥11 km	Unsuitable
	Distance to substation	≤6 km	4 km	High suitable
		7-12 km	8,5 km	Medium suitable
		≥13 km	≥13 km	Unsuitable
Transportation	Distance to motorways	≤2,5 km	1,25 km	High suitable
		2,6-5 km	3,45 km	Medium suitable
		≥5 km	3,60 km	Low suitable

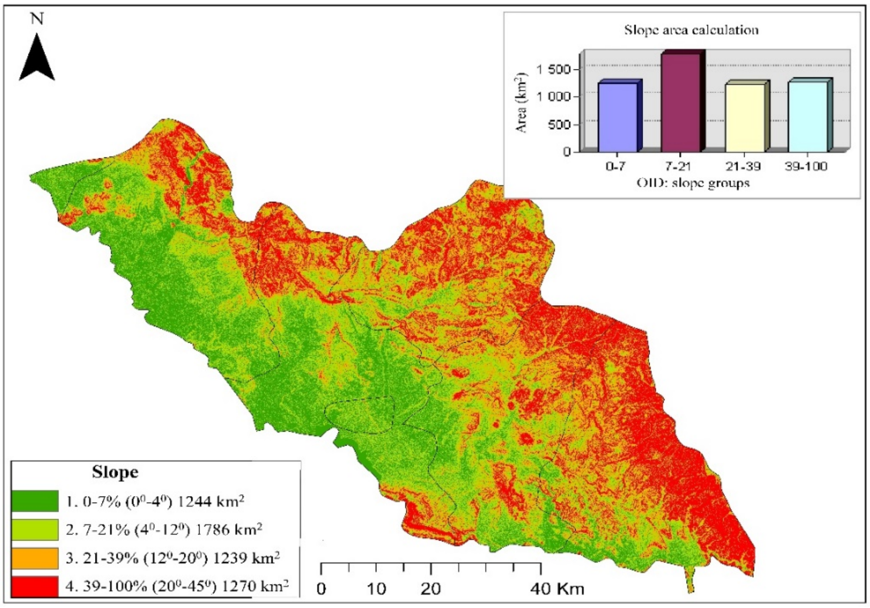

Figure 5 – Slope map of the Nakhchivan AR (Earth Data Search, 2020)

The distance to substations and power lines plays an important role in choosing the most suitable location for installing solar power plants in terms of preventing energy losses and additional costs. Based on this argument, the optimal distance from the planned sites to substations and power lines should not exceed 6 km, as this significantly increases the initial investment costs (Noorollahi et al., 2016). Locations, where the distance to the substation and the power grid is less than 2000 m, are considered very suitable for installing solar power plants, however, areas between 2001-4000 m are moderately suitable, 4001-6000 m less suitable, 6001 m and over are unsuitable (fig. 6).

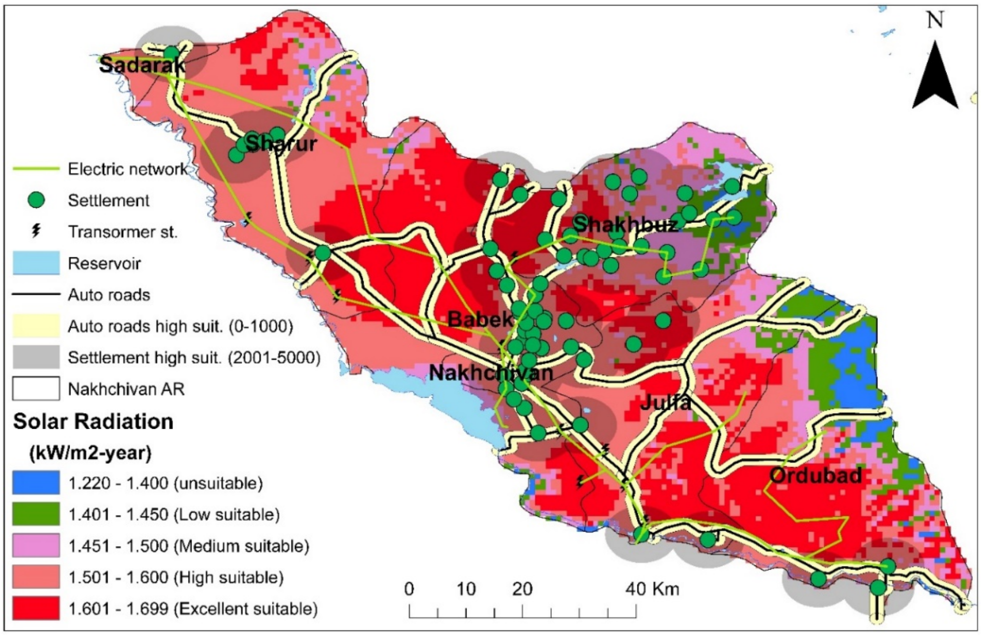

Figure 6 – Suitability map for choosing a solar power plant installation site

The total indicator values for all areas with these four different distance values were calculated using a weighted AHP model.

The presence of a motorway in the area intended for the installation of a solar power plant is considered an economic criterion in terms of preventing additional investments for the transport of solar energy units. Placing stations near roads reduces the additional costs of infrastructure work such as highway construction, and also prevents damage to the environment and landscape (Al Garni & Awasthi, 2017). As shown in map 5, the distance from 0 to 1000 m is indicated as 4 (high suitable), from 1001 to 3000 m – 3 (medium suitable), from 3001 to 5000 m – 2 (low suitable), from 7001 m and above was marked as 1 (unsuitable).

All data from 4 main criteria and 14 subcriteria weighted in the study were analyzed. In the AHP model, the eligible places, which were determined by applying a pairwise comparison matrix, were ranked in 4 categories from high to low. The consistency factor of pairwise comparisons was calculated to test all weighted CR values and found to be at 0.086 (value judgment, 0.10). Then, using the model builder modelling feature in the ArcMap software, weighted criteria were added to areas of high total solar irradiance on the horizontal surface and the suitability of the site for solar PV was determined (fig. 7).

Based on the total amount of total solar radiation on a horizontal surface in Nakhchivan, the possibility of generating electricity from photovoltaic panels was calculated. For example, in the Babek region, the annual value of the total solar radiation on a horizontal surface is 1597 kWh/m^2 and the average annual maximum electricity production per 1 m^2 of a solar panel will be 180 kWh (efficiency, 15%).

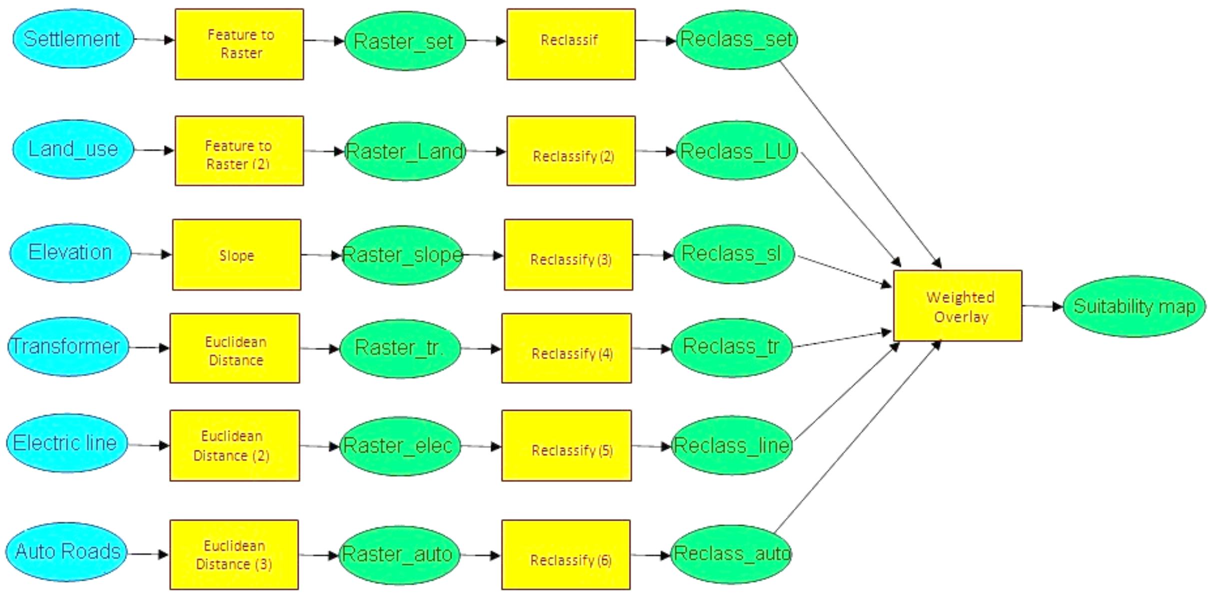

Figure 7 – Weighting the basic criteria for suitable sites selection with a model builder

Conclusion

In Nakhchivan, suitable locations for the installation of power plants in areas with high total solar radiation on the horizontal surface as a result of the study using the AHP model are divided into three categories: high suitability, medium suitability and low suitability.

- As a result of a weighted overlay tool of certain criteria, using the ArcMap model builder modelling, it was found that 9.5% (510 km^2) of Nakhchivan correspond to areas most suitable for placing solar power plants (fig. 7);

- It was concluded that the areas with medium and low suitability for the installation of solar power plants in the region are 12% (645 km^2) and 24% (1290 km^2), respectively;

- 54.5% of the study area (2930 km^2) does not meet the site selection criteria (fig. 6), the primary reasons for which are low total radiation level, high cloudiness, protected areas, soil fertility, poor infrastructure and unsuitability terrain;

- Spatial, metrological, environmental and infrastructure-related indicators (solar radiation, slope, land use, electricity grid, transport) used to determine the suitability of solar energy use in Nakhchivan are given in table 5. As a result of the analysis of these data, it was concluded that the southern part Julfa, Ordubad and Babek districts are the most optimal territories for installing power plants;

- Total area of 510 km^2 suitable for placing photovoltaic power plants, 109 km^2 are located in the Ordubad region, 98 km^2 in the Julfa region, 124 km^2 in the Babek region, 103 km^2 in the Sharur region and 76 km^2 in the Shahbuz region;

- As a result of the calculation, it is possible to install photovoltaic power plants with a total capacity of 2.55 GW on an area of 510 km^2 (approximately 21000 m^2 of land is required for a 1 MW solar power plant). These power plants can generate 38.1 billion kWh of electricity per year, which is about 1.5 times the total electricity production in the country. This will not only make the region predominantly important in terms of energy security but also allow the region to be environmentally friendly, prevent global warming and air pollution, not harm human health, support economic growth and increase competitiveness.

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