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GIS- and AHP-based Decision Systems for Evaluating Optimal Locations of Photovoltaic Power Plants: Case Study of Republic of North Macedonia

Abstract: This study employs a geographic information system (GIS) and an analytical hierarchy process (AHP) to identify optimal locations for photovoltaic (PV) solar farms in the Republic of North Macedonia. It assesses land suitability using six criteria (solar irradiance, aspect, slope, distance from power lines, roads, and urban areas) and six constraints (urban settlements, agricultural zones, national parks, water bodies, steep slopes, elevations above 1500 m). A suitability map was created using a matrix of pairwise comparisons, and the weights for each criterion were calculated. The map was divided into four categories: highly suitable, suitable, less suitable, and unsuitable. The results showed that 11.6% of the study area was classified as being highly suitable, 40.1% as suitable, 3.6% as less suitable, and 0.8% as unsuitable. Additionally, restricted areas (comprised of national parks, residential and agricultural lands, elevations above 1500 m, and water surfaces with 1000 m buffer zones) accounted for 43.7% of the study area. Utilizing just 0.6% of highly suitable land for PV technology could generate approximately 2870 GWh annually, enough to meet the average electricity needs of the industrial sector across the eight administrative regions of R. N. Macedonia. The study offers a replicable GIS-based approach for solar energy planning, contributing to sustainable development and providing insights for integrating solar PV systems into the national energy strategy.

Keywords: multi-criteria decision analysis (MCDA), renewable energy, solar farm, suitability map, sustainable energy planning

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1. Introduction

As a member of the Western Balkan Contracting Parity of Energy Community, R. N. Macedonia is committed to achieving the goal of climate neutrality by 2050 [1]. To this end, the country has been working to make its development more environmentally friendly; in 2020, it became the first Western Balkan nation to submit its National Energy and Climate Plan to the Energy Community for review. Additionally, R. N. Macedonia has implemented its Energy Development Strategy 2040 and improved its Nationally Determined Contribution, which aims to reduce greenhouse gas emissions by 30% by 2030 [2]. To promote the use of renewable energy sources, the country has implemented various incentive programs and household subsidies. Furthermore, it has been aligning its energy efficiency laws with European Union (EU) requirements and providing subsidies to a limited number of households in order to upgrade their energy efficiency levels [3]. However, a challenge has emerged in the form of solar energy curtailment – a consequence of its unpredictable nature that can lead to inefficiencies in energy supplies and grid management.

To ensure a fully green recovery and reduce the dependency on fossil fuels, solar PV plants are expected to be developed across the territory of R. N. Macedonia [1]. The first significant solar plant in the country (with a 10 MW installed capacity) was built by public company Elektrani na Severna Makedonija (ESM) and is already generating clean electricity [2]. The main challenge in achieving the target in solar energy development is identifying optimal locations where PV power plants can be installed – considering multiple criteria such as economic, socio-political, and environmental hurdles [4]. To address this challenge and support the adoption of renewable energy sources, it is essential for the government to prioritize the development of a planning tool for identifying the optimal locations for PV power plants.

GIS software is commonly used to analyze site-selection problems that involve spatial dimensions [5–8]. Prior to selecting a site, one must identify the criteria that are most important. Often, such criteria are chosen by asking the experts (through interviews, or indirectly through a literature search) [9]. This process is known as multi-criteria decision analysis (MCDA) because more than one criterion is considered. There have been numerous applications of MCDA in the energy sector, including energy planning, energy exploitation, site selection, transportation energy management, and many other renewable energy investigations [10–13]. As one of the various MCDA methods, the analytical hierarchy process (AHP) has been widely used along with GIS to evaluate PV power plant site-suitability [14–16]. For example, Uyan [17] and Ziuku et al. [18] used GIS and AHP to analyze the regional suitability of PV solar farms, while Huang et al. [19] used several MCDA methods (including ELECTRE, AHP, and TOPSIS) to analyze energy systems. Heo et al. [20] evaluated a renewable energy scheme using the fuzzy AHP methodology, and Mokarram et al. [21] combined the MCDA method with the Dempster–Shafer theory and a fuzzy system to identify optimal solar farm sites in Fars Province, Iran.

Additionally, La Guardia et al. [22] developed a WebGIS tool, integrating multi-criteria analysis with GIS for the localizations of P2G plants in Sicily, Italy, thus demonstrating the application of geomatics in renewable energy site selection.

The most common factors in PV farm-site selection have been detailed in several review publications [23–26]. Halder et al. [27] identified solar radiation as the most crucial factor, followed by land-surface temperature, residential area, power line, soil type, proximity to key roads, slope, and aspect. This prioritization is consequential because, after the fundamental consideration of solar radiation, other factors such as land-surface temperature and infrastructure proximity become critical in regional studies for practical and logistical reasons. For instance, Sánchez-Lozano et al. [28] and Solangi et al. [29] both highlighted proximity to a power grid as the most significant criterion.

While AHP and GIS are widely recognized in MCDM for PV site selection, alternative methods such as ELECTRE, TOPSIS, and fuzzy logic-based approaches [19–21] offer varied perspectives on handling complex criteria. The choices of AHP (known for its structured decision-making framework) and GIS (for its spatial analysis capabilities) have been driven by their proven effectiveness in simplifying complex multi-criteria evaluations, making the process more accessible to the diverse range of stakeholders that are involved in renewable energy planning.

A summary of previous studies that explored suitability and site-selection assessments for PV systems using an MCDA method in a GIS environment is presented in Table 1.

Table 1. Review of literature on solar power plant selection using MCDA and GIS methods

Reference	MCDA method	Plant type	Location	Criteria
Sánchez-Lozano et al. [28]	AHP, TOPSIS	PV power plant	Southeastern Spain	Agrological capacity, land slope, land orientation, plot areas, distance from villages, distance from main roads, distance from substations, distance from power lines, solar irradiation potential, average temperature
Isiaka et al. [30]	AHP	PV power plant	Nigeria	Global horizontal irradiance, annual average temperature, elevation, slope, aspect, distance from powerlines, distance from rivers, distance from major roads, distance from urban areas
Suh and Brownson [31]	Fuzzy-AHP	PV power plant	South Korea	Solar irradiation, equivalent sunshine hours, average summer temperature, 3D path distance from nearest transmission line, 3D path distance from nearest road, slope, area

Table 1. cont.

Reference	MCDA method	Plant type	Location	Criteria
Aly et al. [32]	AHP	PV power plant and concentrated solar power	Tanzania	Solar resources, water availability, accessibility, demand, PV technology
Yousefi et al. [33]	Boolean-Fuzzy	PV power plant	Iran	Distance from faults, distance from roads, distance from urban and rural areas, slope, elevation, land use, distance from rivers and lakes, hours of available sunshine
Akkas et al. [34]	AHP, ELECTRE, TOPSIS, and VIKOR	PV power plant	Turkey	Solar energy potential, allocated feeder connection capacity, surface slope
Ziuku et al. [18]	AHP	Concentrated solar power	Zimbabwe	Solar radiation, land use, water bodies, power lines, land slope

By reviewing the literature, several of the variables that have been used in GIS-based PV farm site-selection studies can be grouped into two criteria: constraint variables that restrict project-site selection, and factor variables that assess the values with high suitability for PV-site development (Fig. 1) [18, 30, 32, 33]. This dual consideration of constraints and factor variables highlights a methodical approach that not only respects environmental integrity but also seeks to optimize the technical potential for solar energy production, ensuring that the chosen sites for PV farms are both environmentally sound and technically viable. The strategic balance between these variable types is crucial; it allows for the careful alignment of PV farm development with the overarching goals of environmental conservation and renewable energy production. The final criteria for selecting PV farm sites were determined based on consultations with experts on solar PV farms to identify the most relevant factor criteria that were associated with the territory of R. N. Macedonia.

As a result, all of the information was synthesized, the criteria were selected, and a preliminary list was determined. The evaluation of the preliminary list was based on technical and economic factors. The amount of solar radiation that a site receives, the aspect, and the slope of a potential site are among the technical feasibility factors. Economic variables such as proximity to urban areas, roads, and power grid were chosen because they defined the project costs that are connected with PV solar farms. On the other hand, restricted areas such as national parks, urban settlements, agricultural areas, elevations above 1500 m, and water surfaces with a buffer zone of 1000 m were excluded from the study area.

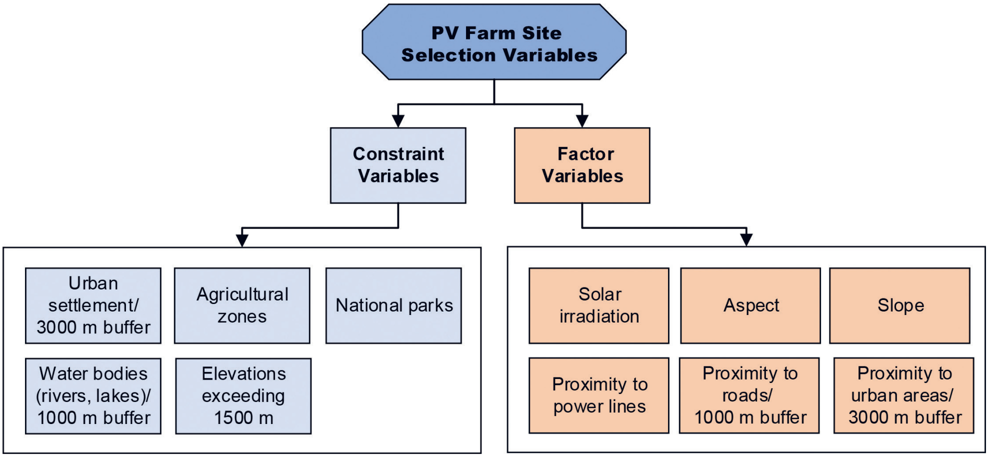

Fig. 1. Variable classifications for GIS-based PV farm-site selection

While this study primarily focused on technical and economic factors, the significance of social factors and regulatory guidelines in the broader context of the adoption of PV technology was recognized. Given their complexity and the need for separate in-depth analyses, however, these aspects were not included in the current scope. Social acceptance, community impact, and compliance with environmental regulations are acknowledged as being crucial for the sustainable implementation of PV projects. These elements will form an essential part of future research to comprehensively address the multifaceted nature of PV technology deployment.

Although the MCDM method has been used in many studies to identify the optimal locations of PV farms, no study has applied this method using GIS and AHP to build a large national-scale GIS database of optimal PV power plant locations in R. N. Macedonia. Given its abundant solar energy resources, the country has the potential to increase its energy independence, reduce pollution, meet its climate commitments, and increase regional electricity exports. Using the proposed methodology, a location-suitability map was created for the country, dividing it into four prospective location groups (highly suitable, suitable, less suitable, and unsuitable) based on compound site indexes that were generated by using a GIS application.

2. Materials and Methodology

2.1. Study Area

The current study was done in R. N. Macedonia, bounded by latitudes 40° and 42° N and mostly between longitudes 20° and 23° E; this covered a total area of 25,713 km^2 (Fig. 2). The capital city of R. N. Macedonia is Skopje. Located in a mountainous region and surrounded by a steep hillside, R. N. Macedonia has a unique climate. Combined with the influence of the Black Sea, a Mediterranean climate prevails in the plains. Additionally, the mountains in the south prevent warm air from migrating to the north, thereby giving the country its continental character. The mean annual temperature is 11.5°C, but the plains experience a higher temperature (around 15°C) [35].

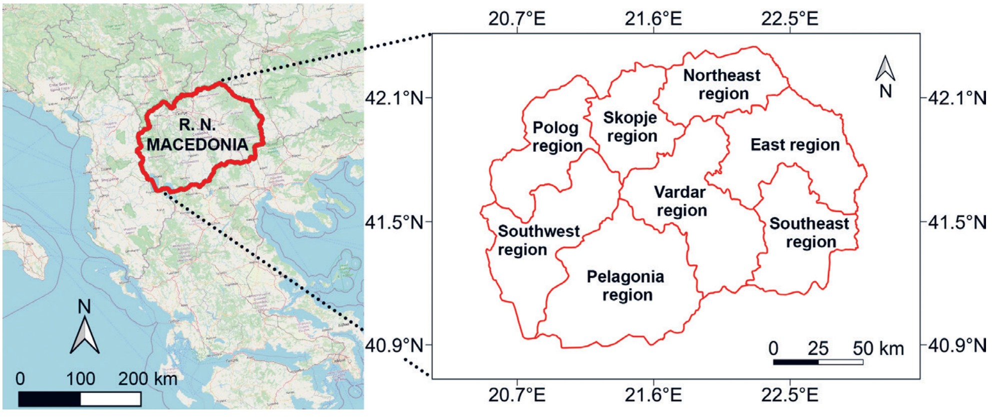

Fig. 2. Location map of study area, along with administrative regions

In addition to its geographical location and climate, the country has an average of 280 days of sunshine per year, which provides ideal conditions for solar energy production [36]. In the northern part of the country, the average daily solar radiation is 3.4 KWh/m^2, while the average is 4.2 KWh/m^2 in the southwest part. R. N. Macedonia has an average annual electricity consumption of 6.42 billion kWh, of which 30% is imported [2]. The electric power-generation capacity in R. N. Macedonia is mainly composed of two thermal power plants, with a total installed capacity of 800 MW. The total capacities of the renewable energy sources are around 780 MW, which consist of eight large hydropower plants (with a total installed capacity of 587 MW), small hydropower plants (with an installed capacity of around 106 MW), wind power (around 37 MW), and solar power (around 30 MW) [2]. Additionally, this region's climate provides favorable conditions for the successful development of solar energy due to the high levels of solar radiation, temperature, and humidity.

2.2. Methodological Framework

An investigation was carried out to evaluate the optimal locations of PV power plants in R. N. Macedonia using the proposed methodology (Fig. 3).

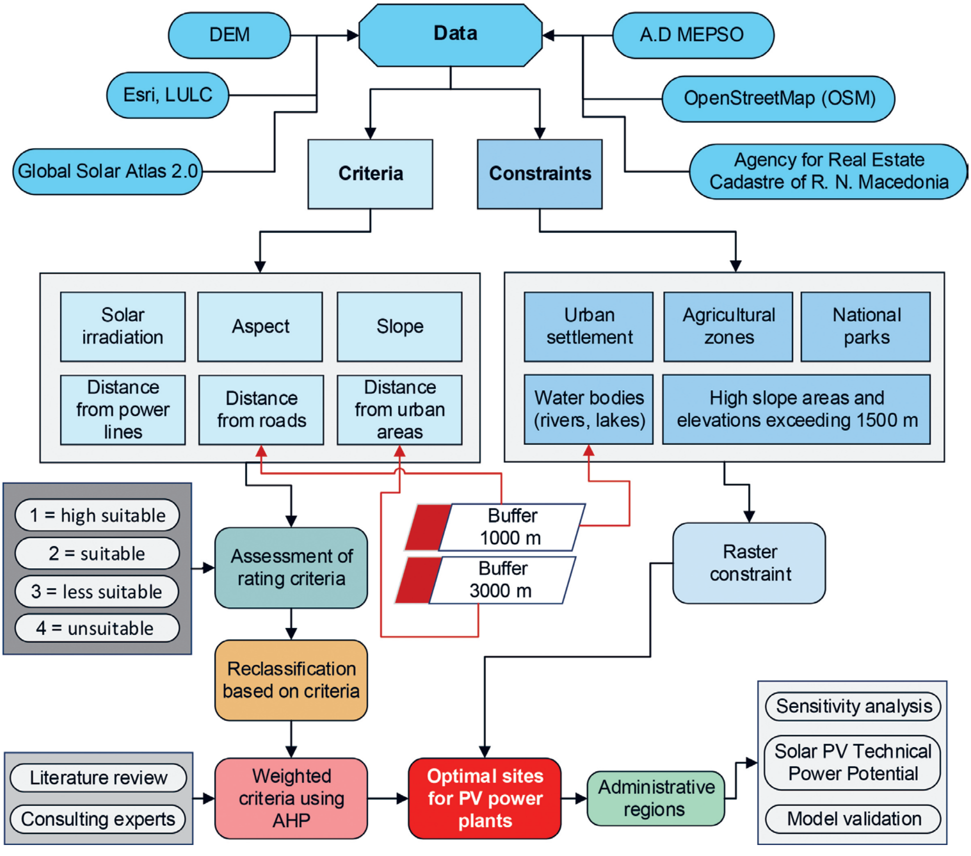

Fig. 3. Methodology scheme and workflow for generating optimal sites for PV power plants

The methodology began with collecting data from various open sources, including satellite images, digital elevation models (DEM), solar radiation data, land use and land cover (LULC) (urban areas, agricultural lands), OpenStreetMap data (roads, water bodies, national parks), and powerlines data. This was followed by analyzing and identifying six criteria that affected the location choice for PV power plants. The geodata of these criteria were imported into QGIS, reclassified based on weighted values, and assessed using the AHP method in order to determine their relative rankings. The process involved the creation of a map to show the optimal areas for establishing PV power plants (categorized into four suitability classes). The unsuitable locations were identified and excluded based on the constraints. The final map was used to calculate the area for each class and the total technical power potential for large-scale PV plants in the highly suitable zones of each administrative area. The methodology also included performing a sensitivity analysis to evaluate the impact of changing the criteria's relative importance, which aided in addressing potential inconsistencies and identifying key criteria. Finally, validating the suitability map was necessary for ensuring the accuracy and reliability of the identified sites.

2.3. Data Collection, Selection of Criteria, and Restrictions

Various websites were used to identify the criteria, which were then reclassified based on estimates. Table 2 presents the selected criterion and constraint variables that were selected for this study, along with their references and original data sources. Figure 4 illustrates a detailed visual representation of the criterion and constraint maps, essential for the selection of PV power plant sites. These criteria were chosen based on a literature review, expert opinions, and accessibility to a geo-referencing database.

Table 2. List of criteria, constraints, data extension, and data sources

	Factors	Threshold	Data source
Criteria	Solar irradiation	Itself	© 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis
	Aspect	Itself	Copernicus Land Monitoring Service – EU-DEM
	Slope	Itself	Copernicus Land Monitoring Service – EU-DEM
	Distance from power lines	Itself	A.D MEPSO
	Distance from roads	1000 m buffer	OpenStreetMap (OSM) https://www.openstreetmap.org/
	Distance from urban areas	3000 m buffer	© 2022 Esri, Microsoft, Global land use/land cover with Sentinel-2 and deep learning
Constraints	Urban settlement	3000 m buffer	© 2022 Esri, Microsoft, Global land use/land cover with Sentinel-2 and deep learning
	Agricultural zones	Itself	© 2022 Esri, Microsoft, Global land use/land cover with Sentinel-2 and deep learning
	National parks	Itself	Agency for Real Estate Cadastre of R. N. Macedonia
	Water bodies (rivers, lakes)	1000 m buffer	OpenStreetMap (OSM) https://www.openstreetmap.org/
	Elevations exceeding 1500 m	>1500	Copernicus Land Monitoring Service – EU-DEM

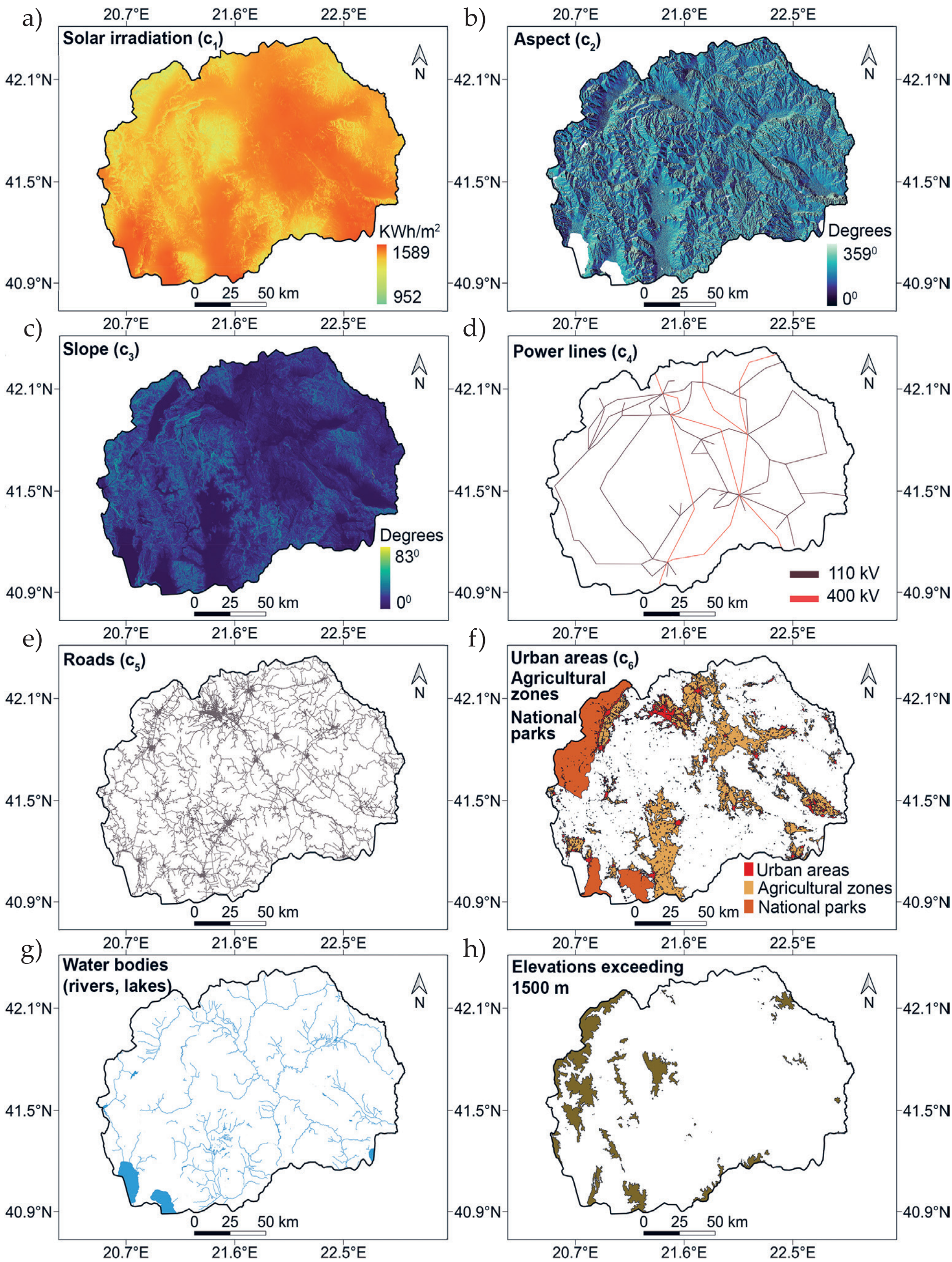

Fig. 4. Criterion and constraint maps for selecting PV power plant sites: a) solar irradiation (c_1); b) aspect (c_2); c) slope (c_3); d) power lines (110 kV and 400 kV) (c_4); e) roads (c_5); f) urban areas (c_6), agricultural zones, national parks (constraint map); g) water bodies (constraint map); h) elevations exceeding 1500 m (constraint map)

This study suggests the following six criteria for assessing potential PV power plant sites while considering the specific orographic, environmental, and economic characteristics of each region (Fig. 4a–f):

1) solar irradiation (measured as global horizontal irradiance [GHI]),
2) aspect (orientation),
3) slope,
4) distance from power lines (110 kV and 400 kV),
5) distance from roads,
6) distance from urban areas.

Environmental and engineering constraints may limit the development of PV solar energy under certain conditions or in certain areas. To minimize the impact of PV systems on local environments, those areas that have been designated as environmental protection zones, national park conservation zones, agricultural zones, and other development zones as specified by local laws were identified and excluded from the selection process (Fig. 4f, g) [37, 38]. Additionally, buffer zones from urban settlements, rivers, lakes, and roads were considered, and high slope areas and elevations above 1500 m were avoided due to their low economic viability for such projects (Fig. 4h).

The constraint variables were combined to create a unified constraint raster layer. Here is a description of each of these selected criteria:

– Solar irradiation (c_1)
  The continuous operation of PV power plants requires sufficient solar radiation, which is typically expressed as an average over several years and is used to evaluate a site's sunshine intensity. GHI is the total amount of shortwave radiation that is received by a horizontal surface on the ground and is directly proportional to PV power output [39]. Solar irradiation is crucial for converting solar radiation to electricity through PV technology, which relies on the PV effect in semiconductors to directly convert solar radiation into electricity.
– Aspect (c_2)
  The direction of a land slope is described by its aspect, which is a topographical feature. It is represented by an azimuth angle, which ranges from 0° to 360°. For this study, the aspects that were considered included south, southeast, southwest, east, west, northeast, northwest, and north. Importantly, the south, southeast, and southwest directions were found to be the most suitable for the placement of PV solar power plants [40]. This preference was due to the angle of solar incidence: in the northern hemisphere (where the latitudes affect the angles of the sun's rays), these orientations receive the highest amount of direct sunlight throughout the year, maximizing solar energy absorption. Conversely, the other directions were considered but given lower ratings due to their reduced exposures to optimal sunlight.

- Slope (c_3)
  The slope of a site (or its inclination percentage) is an important factor when determining its suitability for a PV power plant [41]. Flat areas are generally more suitable than steep slopes, and the DEM for the study area was used to determine the percentages of slopes and their topographic orientations (aspects).
- Distance from power lines (c_4)
  Proximity to existing distribution and transmission power lines can reduce transmission losses and eliminate the need for costly new infrastructure [42]. For this reason, areas that were close to 110 kV and 400 kV transmission lines were given a highly suitable rating in the power-grid criteria.
- Distance from roads (c_5)
  Accessibility and proximity to roads are important considerations when selecting the best sites for PV power plants, as they facilitate the transportation of equipment and modules and make maintenance easier during and after construction [43]. Using the Euclidean Proximity method, a maximum radius of 12 km from road lines was considered. To ensure safety and protect solar panels from non-neutral dust sources and potential road expansion, a buffer of 1000 m from each side of every major road was added. With safety as a priority, it was possible to calculate gradually optimum distances that were yet close enough to the PV power plants for workers and maintenance trucks to move around with ease.
- Distance from urban areas (c_6)
  It can be more economical to locate PV power plants near populated areas, as they can deliver power to nearby clients with minimal transmission losses [44]. As part of the efforts to reduce adverse environmental impacts on the growth and population of urban areas, a 3000 m buffer was added (which needed to be excluded from the calculations).

2.4. Rating Criteria

As part of analyzing the PV site-suitability of R. N. Macedonia through comparisons, the six previously mentioned criteria were assigned ratings of 1, 2, 3, and 4:
1) highly suitable,
2) suitable,
3) less suitable,
4) unsuitable.

Due to their efficiency in the sunlight zone, PV systems require at least 4 kWh/m^2/day of solar irradiance in order to be economically feasible [45].

Previous studies on PV site-suitability have found that slopes that are greater than 3% or >21° are unsuitable, as the adjacent rows of a PV system will be shaded (thus reducing the site's efficiency and impacting its economic viability) [41, 43, 45]. In this study, only areas with slopes that were less than 21° and properly oriented were rated. Additionally, locations that were less than 12 km from main roads and power transmission lines were given ratings for the potential installations of PV power plants. Also rated for the possibilities of installing PV power plants were those areas that were less than 30 km from urban areas.

The reclassified layers of the site-suitability criteria for deploying PV power plants in R. N. Macedonia are shown in Figure 5a–f.

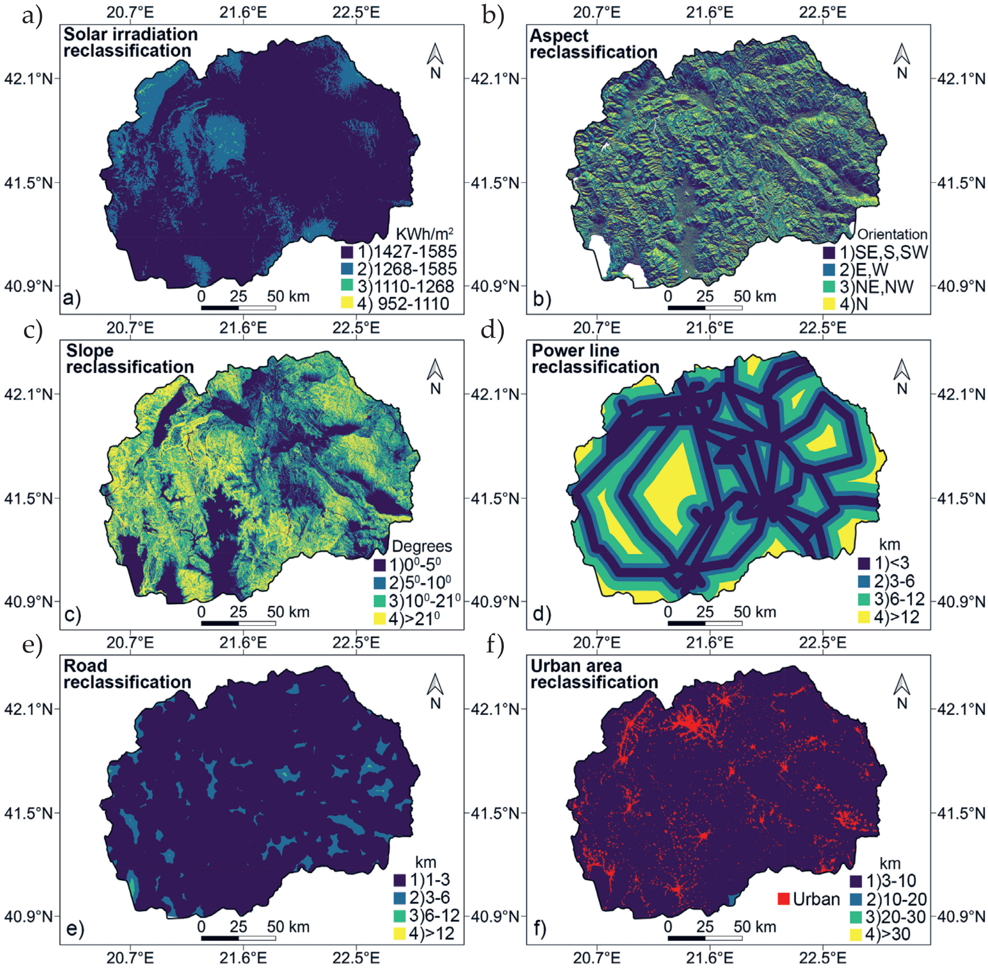

Fig. 5. Reclassified layers of input criteria, ranging from Class 1 (with highly suitable values) up to Class 4 (referring to unsuitable conditions for deploying PV power plants: a) solar irradiation reclassification; b) aspect reclassification; c) slope reclassification; d) power line reclassification; e) road reclassification; f) urban area reclassification

2.5. Weighting Criteria using AHP Technique

In order to find suitable sites for PV power plants, several criteria and multiple objectives must be considered; this can result in a complex decision-making process. MCDM methods offer a logical framework for examining, analyzing, and solving such problems. In this study, a utility function-based MCDM method called AHP (which has been successfully used to address a variety of decision-making issues in areas including renewable energy analysis) was employed. Three underlying concepts underpin AHP: structuring complex decision problems into hierarchies of goals, criteria, and alternatives; comparing the elements at each level of a hierarchy with each criterion at the previous level; and aggregating the judgments from all levels [46].

AHP uses the pairwise-comparison technique to homogenize the influences on a unity sum and identify the chosen weighted scores of a criterion. According to Saaty [46], the AHP has been employed, particularly in his work, to estimate the weight of each criterion. After that, a pairwise comparison matrix analysis was used to determine the weighted values for each criterion. In the pairwise comparison matrix approach (Table 3), the weighted score was divided into ranges of 1 to 9, with the low (1) and high (9) values being noted. Experts were asked to assign a weight score based on their experiences for each factor variable using a comparison matrix.

Table 3. Fundamental scale and their clarification for pairwise comparison

Intensity of importance	Grade definition by relative importance	Explanation
1	Equally important	Both criteria equally contribute to objective
3	Moderate importance of one over another	Experience and judgement slightly favor one criterion over another
5	Strong or essential importance	Experience and judgment have medium tendency to favor one criterion over another
7	Very strong or demonstrated importance	One criterion is strongly favored over another, and its dominance is established in practice
9	Extreme importance	Contribution of one criterion over another is of highest possible order of affirmation
2, 4, 6, 8	Intermediate values	Intermediate values for compromise between above values

Source: acc. to [47]

The reclassified layers of the site-suitability criteria for deploying PV power plants in R. N. Macedonia are shown in Figure 5a–f.

The weights of all of the criteria in a pairwise comparison add up to 1. For instance, a 6 × 6 matrix is needed in this case to estimate the weights of the six criteria.

Paired comparison matrix A is shown in Equation (1), where c_{ij} represents the relative importance of criterion c_i over criterion c_j according to Table 3:

$$A = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{bmatrix} \tag{1}$$

The reciprocal judgement states that, if criterion c_i is more important than criterion c_j by k, then the relative importance of c_j over c_i is $1/k$.

Thus, $c_{ij} = 1/c_{ij}\ \forall\ i \neq j$ and $c_{ij} = 1$ for $i, j = 1, 2, ..., n$ in matrix A, where the term 'reciprocal matrix' refers to such a defined matrix. Such a matrix requires a certain number of judgments, which is $n(n - 1)/2$. With the judgment matrix constructed, the priority vector can be calculated with the eigenvalue method [46–47]:

$$A \cdot w = \lambda_{\max} \cdot w \tag{2}$$

where $\lambda_{\max}$ is the maximal eigenvalue. In this case, the priority vector indicates the importance of each criterion and how it impacts the overall goal in finding the optimal PV power plant sites. Pairwise criteria comparisons may lead to inconsistent results, so an inconsistency check must be performed.

In order to calculate the maximum principal eigenvalue $\lambda_{\max}$ of the matrix, the following equation must be solved:

$$\det(A - \lambda I) = 0 \tag{3}$$

where I represent the $n \times n$ identity matrix. Judgment matrix A can be consistent if $c_{ik} = c_{ij}c_{jk}\ \ \forall\ i, j, k$. Due to the inherent inconsistency of human judgments, this condition is difficult to fulfill. The consistency index (CI) and consistency ratio (CR) need to be calculated in accordance with Equations (4) and (5) in order to determine the matrix's degree of consistency [48]. If the CR value falls below the 0.1 threshold, the matrix is considered to be consistent, while the matrix is regarded as being inconsistent if CR goes above this value [48]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{4}$$

$$CR = \frac{CI}{RI} \tag{5}$$

The matrix size affects the random index values (*RI*) that are shown in Table 4; these are used to calculate *CR*. The consistency adjustment methodology that was suggested by Saaty [48] (based on a maximum deviation approach) is used when the individual matrix turns out to be inconsistent; i.e., $CR > 0.1$.

Table 4. Random index values

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Source: acc. to [48]

2.6. Generating Suitability Map

In the context of location-selection, weighted sum raster overlay analysis (WSROA) is a useful technique for determining the suitability of a site based on the overall dimension of the different and dissimilar impacts. To calculate the potential PV power plant sites, all of the criteria were overlaid in QGIS software using the WSROA technique. The overall criteria were transformed into rasters, and most of the arrangements were made using QGIS. WSROA uses a weighted value of each pixel to calculate the site-selection for a pixel-based analysis. The PV power plant suitability map was calculated using Equation (6) [27, 45]:

$$S = \sum_{i=1}^{n} w_i x_i \tag{6}$$

where:

S – suitable PV power plant sites,
w_i – weight of criteria i,
x_i – standardized score of the criteria,
n – overall number of criteria that were chosen for the PV power plant sites.

2.7. Solar PV Technical Power Potential Model

Assessing the feasible solar PV technical potential (or the maximum power capacity that can be installed without causing environmental and social impacts) involves the exclusion of restricted areas and those areas that are unsuitable for utility-scale PV systems within the defined boundaries. This process is the first step in determining the potential for solar PV development in a given country. It is important to note that the area that is required to produce one MW of solar power can vary depending on the technology that is used for the conversion as well as the regional GHI value [49]. As such, the yearly electric power-generation potential (E_i) for each administrative region in R. N. Macedonia can be estimated using the following equation [50]:

$$E_i = G_i \cdot A \cdot A_f \cdot \eta \cdot pr \tag{7}$$

where:

E_i – electric power-generation potential per year [MWh/year],
G_i – annual solar radiation received per unit horizontal area [kWh/km^2/year],
A – calculated available or suitable land area for deploying solar farms [km^2],
A_f – area factor indicating what fraction of calculated areas can be covered by solar panels (assumed to be 10%) [49],
η – efficiency with which solar system converts sunlight into electricity,
pr – 0.77 (performance ratio of PV system) taking energy loss in storage and connection into electricity grid into account [51].

A PV cell's efficiency can differ depending on its technology [52]. A high-efficiency tandem cell (which has an efficiency of 36.1 to 41.1%) has the highest conversion efficiency according to the Fraunhofer Institution. C-Si cells range in efficiency from 20 to 24%, while simple cells range from 14 to 18%. On the other hand, thin-film cells have lower efficiency rates (ranging from 6 to 11%). Existing PV projects generally have efficiencies between 11 and 15%; as a result, this study uses a value of 14.3% efficiency.

2.8. Sensitivity Analysis

The AHP technique is based on expert opinions for the pairwise comparisons of criteria (which can be subject to subjectivity). This subjectivity is a major disadvantage of the AHP technique – especially in pairwise comparisons [53]. In some contexts, AHP may yield less-refined rankings for competing candidates – particularly when identifying the major contributors to a specific problem [53]. In order to address the subjectivity of criterion weights and the potential uncertainty of model outcomes, previous studies have suggested using the Monte Carlo simulation (MCS) in conjunction with conventional AHP in order to improve the screening process when identifying reliable decision alternatives [54, 55]. The application of this method is beyond the scope of this study, so two scenarios will be conducted in the sensitivity analysis: in the first scenario, equal weight is given to each criterion; and in the second scenario, only GHI, aspect, and slope criteria are considered to identify the most-suitable areas for electricity production from PV systems. As a result of this analysis, the area of the regions that are highly suitable for PV plants will be increased as compared to the original results.

By excluding specific input criteria from the AHP algorithm, however, the sensitivity analysis requires us to keep the relative weightings of the other criteria unchanged. This can lead to small fluctuations $\Delta \boldsymbol{S}$ in AHP weightings due to possible changes in the pairwise-comparison system [14, 56]. These fluctuations can be accounted for by using the following expression [14]:

$$\Delta S_{i,j} = \frac{S_{i,j} - S_j}{S_j} \cdot 100 \tag{8}$$

where:

$\Delta S_{i,j}$ – change in the percentage in the j_{th} area-suitability class as a result of the excluded assessed i_{th} input criteria (with $i \neq j$),

$S_{i,j}$, S_j – corresponding suitability-class areas with the inclusion and exclusion of the i_{th} input criteria.

3. Results and Discussion

This study developed a GIS/AHP model for identifying optimal sites for establishing PV power plants, assessing each region's suitability, and calculating their technical power potentials. The model integrated six criteria (solar irradiation, aspect, and slope as well as proximity to power lines, roads, and urban areas) using the MCDA/AHP method to determine the weighted values.

Considering GHI to be the sole determining factor of the decision-making, it becomes clear that a large portion of R. N. Macedonia's land would be technically suitable for the installations of PV power plants. Due to the need to maintain protected natural and ecological conservation areas, however, the technically suitable area cannot be fully exploited. The areas that can be used to build PV power plants was drastically reduced (to 56%) when the GIS layer that mapped out the lands with conservation or protected statuses and agricultural fields was excluded from the study (Fig. 4e–h).

Despite the fact that the exclusion of protected areas significantly reduced the search area for the construction of PV power plants, it also decreased the likelihood of those legal barriers that could prevent investments in these kinds of renewable energy technologies.

The AHP results are shown in Table 5; they indicated that GHI had the highest weight (40.9%), followed by slope (29.5%), aspect (11.9%), distance from power lines (8%), distance from roads (5.7%), and distance from urban areas (4.1%).

As the consistency ratio (*CR*) was 0.078, the values were regarded to be stable for the pairwise-comparison technique that was used in this work to delineate PV power plants over the study area.

Table 5. AHP pairwise-comparison matrix for calculating weight allocated to each criterion and *CR* ratio

Criteria	GHI (1)	Aspect (2)	Slope (3)	Distance from power lines (4)	Distance from roads (5)	Distance from urban areas (6)	Weight [%]	*CR*
GHI (1)	1.00	2.00	6.00	5.00	6.00	5.00	40.9	0.078
Aspect (2)	0.50	1.00	4.00	5.00	6.00	5.00	29.5	
Slope (3)	0.17	0.25	1.00	2.00	4.00	3.00	11.9	
Distance from power lines (4)	0.20	0.20	0.50	1.00	2.00	3.00	8.0	
Distance from roads (5)	0.17	0.17	0.25	0.50	1.00	3.00	5.7	
Distance from urban areas (6)	0.20	0.20	0.33	0.33	0.33	1.00	4.1	

Figure 6 shows the suitability map, which identifies those regions in R. N. Macedonia that have highly suitable, suitable, less suitable, and unsuitable conditions for installing PV power plants. The overall area that was classified as having highly suitable conditions was 11.6%, while the remainder were classified as having suitable (40.1%), less suitable (3.6%), and unsuitable (0.8%) conditions.

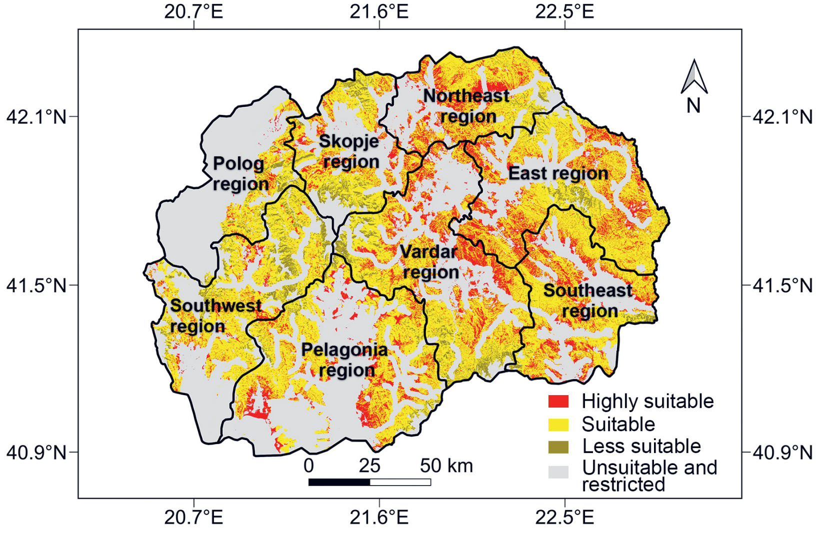

Fig. 6. Map of suitable sites (optimal) for installing PV power plant systems in R. N. Macedonia

Due to a number of the aforementioned natural and human factors, PV power plants cannot be built in restricted zones (which make up around 43.7% of the total area). Additionally, Table 6 provides a detailed summary of the estimated areas for the optimal locations for constructing PV power plants (with the exclusion of constrained areas).

Table 6. Distribution of site suitability and restricted areas, their areas, and their area percentages

Suitability class	Area [km^2]	Area percentage [%]
Highly suitable	2880.0	11.6
Suitable	9955.6	40.1
Less suitable	904.7	3.6
Unsuitable	216.5	0.8
Restricted areas	10,868.1	43.7

When considering the construction of PV power plants in R. N. Macedonia, highly suitable areas should be considered first. The suitability map that was generated for installing PV power plants was statistically analyzed by considering the administrative regions (Fig. 2); this analysis is presented in Table 7.

Table 7. Statistical analysis of suitability map of R. N. Macedonia's administrative areas

Suitability	Vardar region	East region	Southwest region	Southeast region	Pelagonia region	Polog region	Northeast region	Skopje region
Highly suitable [km^2]	596.6	589.5	185.3	415.7	483.3	72.2	344.4	192.6
Suitable [km^2]	1648.5	1746.7	1522.0	1272.5	1592.7	448.3	934.5	790.0
Less suitable [km^2]	186.1	88.3	246.0	46.4	89.1	69.7	42.8	136.1
Unsuitable and restricted areas [km^2]	1498.9	1024.4	1557.1	918.8	2629.0	1813.2	714.4	928.5

The Vardar and East regions of the eight administrative regions had the highest areas of suitability for PV power plant construction, followed by the Pelagonia, Southwest, Southeast, Northeast, Skopje, and Polog regions. Figure 7 shows the spatial variation of the mean annual solar irradiation on the horizon in each administrative region's highly suitable and suitable areas, which is crucial for calculating the annual PV electricity production in each region.

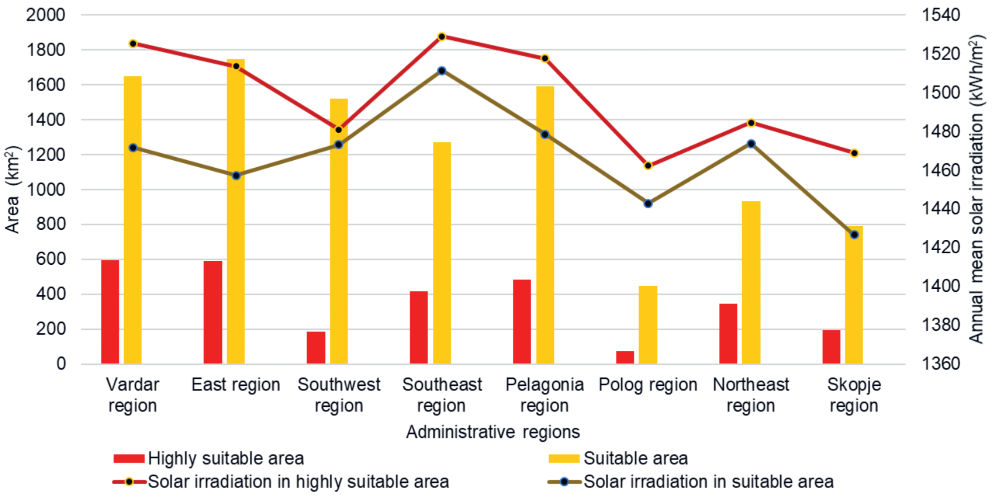

Fig. 7. Administrative regions' highly suitable and suitable areas with mean annual solar irradiation

Those regions that exhibited higher solar irradiation emerged as prime candidates for solar farm development, suggesting that these areas could be prioritized in renewable energy strategies.

The disparities that are highlighted in Figure 7 have direct implications for regional energy planning and sustainable development goals. They underscore the need for a targeted approach to solar energy deployment, where resources are efficiently allocated in order to maximize energy production. For instance, highly suitable regions with high solar irradiation can significantly contribute to the nation's renewable energy targets.

Furthermore, the insights that are gained from Figure 7 can aid policymakers and investors in making informed decisions about where to allocate resources for developing a PV infrastructure. By focusing on those areas with the highest potentials for solar energy generation, efforts can be streamlined; this would potentially lead to the quicker and more cost-effective development of renewable energy projects.

Figure 8 offers a comprehensive view of the interplay between the population distribution and the industrial electricity consumption across the administrative regions of R. N. Macedonia. Approximately 30% of R. N. Macedonia's population is concentrated in the Skopje region; according to Figure 8, however, the region with the highest electricity consumption in the industry sectors between 2018 and 2020 was the Vardar region, followed by the Skopje region [57]. The data that is depicted in Figure 8 reveals those regions with higher levels of industrial activity and, consequently, greater needs for electricity. This information will be crucial for prioritizing those areas where the installation of PV power plants could provide the most significant benefits in terms of energy supply and economic development.

An analysis of the patterns that are shown in Figure 8 identified those regions where the integration of PV systems could effectively support the existing power grid, enhancing energy security and reducing dependency on traditional energy sources. Figure 8 also helps in assessing the feasibility of PV projects in terms of local industrial electricity demands, ensuring that the development of renewable energy resources aligns with actual consumption patterns.

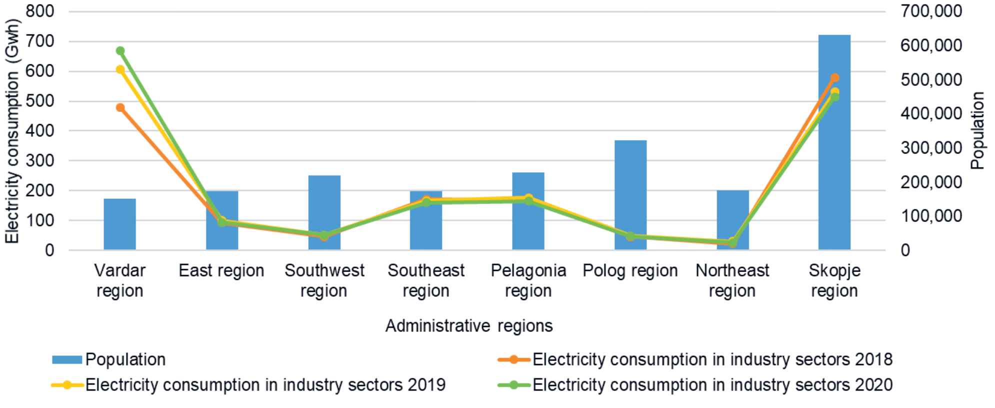

Fig. 8. Population and electricity consumption in industrial sectors for each administrative region in R. N. Macedonia

Figure 9 shows the spatial distribution of the annual technical power potential of PV electricity production in each administrative region's highly suitable and suitable areas (calculated according to Equation (7)).

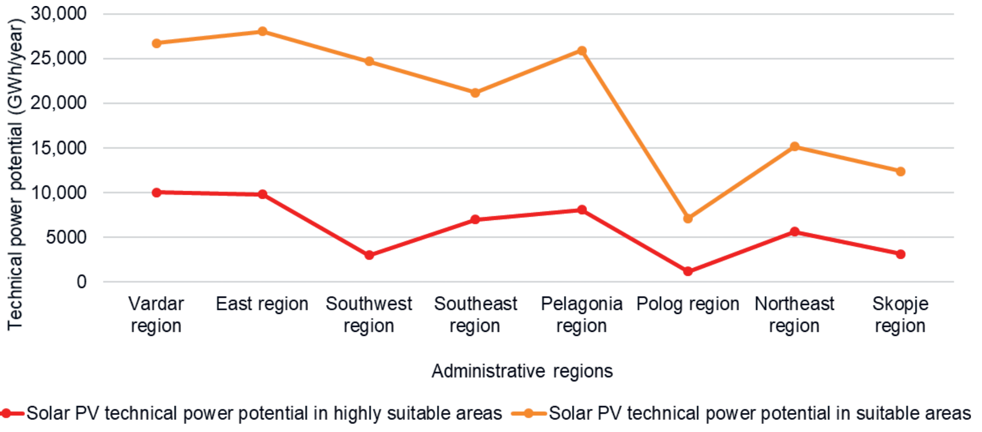

Fig. 9. Administrative regions' technical power potentials of PV power plants [GWh/year], taking only 10% of territory into consideration in highly suitable and suitable areas

Figure 9 provides a critical analysis of the annual technical power potentials for PV electricity production in the highly suitable and suitable areas across each administrative region of R. N. Macedonia. This analysis is pivotal in highlighting the regions with the highest potentials for solar energy generation, thus guiding strategic decisions for future PV plant installations. The visualization of the technical power potentials in the different areas offers insights into where PV development could yield the most significant energy outputs, aligning with the national goals for renewable energy generation.

Furthermore, the analysis that is presented in Figure 9 can assist policymakers and stakeholders in devising a balanced regional energy strategy that takes both the potential and limitations of PV technology in different parts of the country into account. This is crucial for ensuring that the development of renewable energy resources is not only technically feasible but also economically viable and socially beneficial.

The total technical potential for large-scale PV plants installed in 10% of the available area in the highly suitable zones is estimated to be 47,849 GWh. This is 28 times greater than the mean electricity consumption of the industry sectors from 2018 through 2020 (which was 1682 GWh).

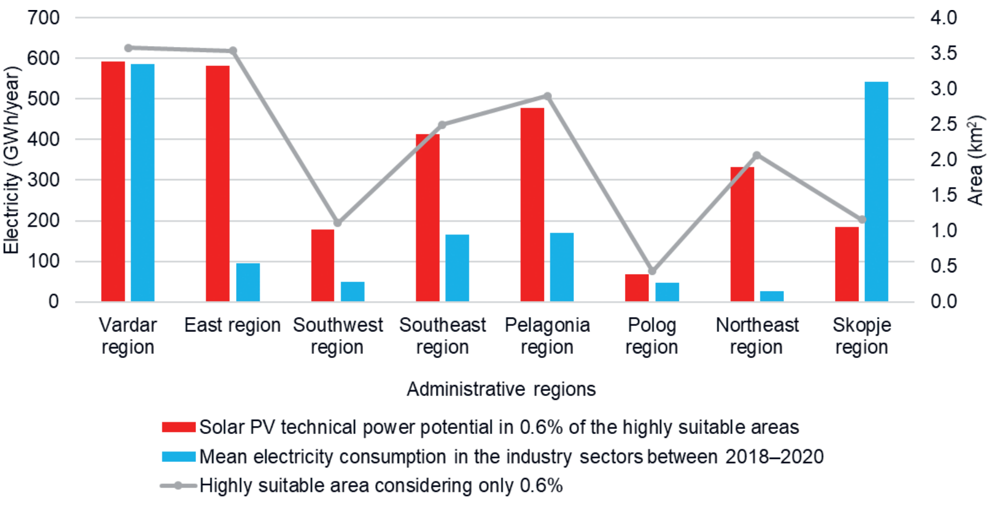

Fig. 10. Administrative region's mean electricity consumption in industry sectors during period of 2018–2020 and technical power potential of PV power plants in 0.6% of highly suitable areas

While the installation of PV plants in 10% of the designated zones in the highly suitable areas is too optimistic, a simulation was made of electricity production in a territory of less than 1% from the selected areas. These results are shown in Figure 10.

To address the intrinsic variability of solar irradiation, a variability adjustment factor (VAF) was introduced into the existing model (Equation (9)). This factor was derived from the standard deviation of the solar irradiation values, providing a more accurate representation of the fluctuating nature of solar energy availability. The approach focused on the period of 2018–2020, allowing for a concise yet robust analysis.

The data for the years of 2018 through 2020 was utilized. The annual irradiation was aggregated for each year, resulting in the following values:

– 2018: 1421.51 kWh/m^2,
– 2019: 1459.01 kWh/m^2,
– 2020: 1452.96 kWh/m^2.

The average annual solar irradiation for these years was calculated to have been approximately 1444.49 kWh/m^2. After measuring the variability in the annual solar irradiation, the standard deviation was found to be approximately 20.13 kWh/m^2. The variability adjustment factor was determined to be the ratio of the standard deviation to the average annual irradiation, yielding a value of approximately 0.014. This VAF of 1.4% reflects the variability around the average annual solar irradiation value for these years.

The modified equation:

$$E_i = (G_i \cdot (1 - VAF)) \cdot A \cdot A_f \cdot \eta \cdot pr \tag{9}$$

incorporates this variability factor, enhancing the accuracy of the estimation of the technical power potential of PV power plants. This adjustment aligns the model more closely with the unpredictability that is inherent in solar energy generation, thus enhancing the robustness of the analysis.

According to Figure 10, it is necessary to install PV systems in a territory of less than 21 km^2 in order to meet the electricity demands of the industry sectors using renewable energy (considering the fact that the Skopje region requires an additional 2.7 km^2 to satisfy its needs).

In order to test the sensitivity of the assigned criteria weights and to confirm the validity of the results, a sensitivity analysis was conducted. During the development of this feasibility study, the possibility of multiple cases meeting the criteria for optimal site selection was considered. In the event of a non-unique solution, the results would indicate the need to adapt the method by adding additional criteria and interpreting the basic data to assist in the decision-making. For instance, decision-makers may choose to alter their plans for constructing new energy infrastructures by taking additional factors into consideration. Another reason is that the influence of specific criteria (or factor variables) on suitability can vary depending on future electricity prices, subsidy policies, and sector developments.

To further evaluate the method, two scenarios were carried out. In the first scenario, each criterion was given equal weight. In the second scenario, only the GHI, aspect, and slope criteria were considered. This allowed us to identify the most suitable areas for electricity production with PV power plants. The results of this sensitivity analysis are presented in Table 8. Additionally, Table 8 shows the difference in the land availability in the highly suitable area class between the results of the original AHP model and the sensitivity analysis.

In Scenario 1, assigning equal weight to each criterion (16.6% per criterion) resulted in a high sensitivity to changes in the criteria weights. Overall, the results of this scenario showed a significant increase in the areas that were classified as highly suitable for PV power plant installations when compared to the original suitability map. This suggests that assigning an equal weight to each criterion leads to a higher concentration of areas within the highly suitable category, with fewer areas falling into the other categories of suitability. In Scenario 2, only solar, slope, and aspect criteria were considered (with weights of 58.8, 32.3, and 8.9%, respectively). This resulted in an increase in the numbers of areas that were classified as highly suitable when compared to the original results. This means that small changes in the weight assigned to a particular criterion can have a significant impact on the results (thus indicating that the model is highly sensitive).

Table 8. Comparison of sensitivity analysis results in highly suitable areas from suitability map

	Suitability map (SM) [km^2]	Scenario 1 (S1) [km^2]	Scenario 2 (S2) [km^2]	Difference (SM – S1) [%]	Difference (SM – S2) [%]
Vardar region	596.6	1038.2	641.6	54.0	7.3
East region	589.5	878.8	731.1	39.4	21.4
Southwest region	185.3	381.5	271.5	69.2	37.7
Southeast region	415.7	672.1	508.7	47.1	20.1
Pelagonia region	483.3	776.7	568.4	46.6	16.2
Polog region	72.2	176.6	83.3	83.9	14.2
Northeast region	344.4	598.4	391.9	53.9	12.9
Skopje region	192.6	418.3	209.2	73.9	8.3

3.1. Model Validation

The suitability map in Figure 6 shows that two of the four zones are suitable for installing PV power plants; however, these results must be validated in order to determine their accuracy. To do this, a validation process was applied to three different areas to see if the zones that were identified as suitable PV sites were appropriate in the real world. Figure 11a–c shows the representative highly suitable zones and corresponding satellite images from Google Earth, which indicated that most of the area in the three sites consisted of highly suitable areas for installing PV power plants, agricultural areas, and urban areas. This suggests that the three sites that were identified on the resulting map can be used for PV plants in the real world.

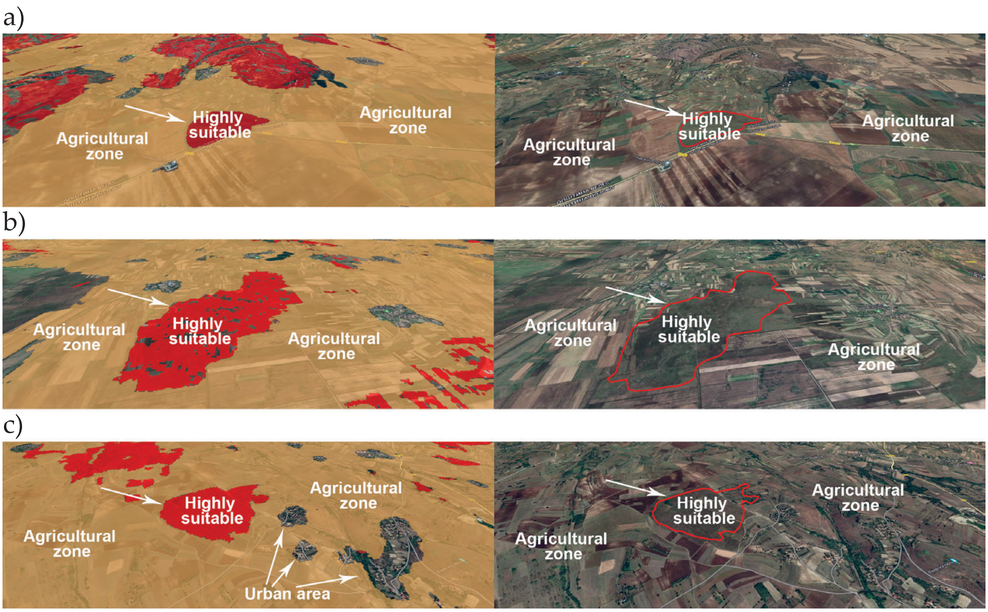

Fig. 11. Google Earth satellite images of three highly suitable areas for validating suitability map results: a) Site 1 – highly suitable area in Vardar region; b) Site 2 – highly suitable area in Pelagonia region; c) Site 3 – highly suitable area in Northeast region

4. Conclusions

Choosing the most suitable locations for PV power plants and high investment costs are two of the key challenges that face the construction of large solar projects. This study examined suitable locations for PV power plants in R. N. Macedonia by integrating an AHP-based MCDA tool with GIS in order to address these concerns. The goal was to identify the most suitable locations for these power plants in order to move forward with their development.

The study analyzed satellite data to identify six criteria that could impact the suitability of an area for a solar farm project (including solar irradiation, aspect, slope, distance from power lines, distance from roads, and distance from urban areas). Additionally, those regions that were unsuitable for solar farms were excluded from the analysis (including urban settlements, agricultural zones, national parks, water bodies, high slope areas, and elevations above 1500 m). The selection of these criteria was based on published research and expert opinions on solar farm performance.

To evaluate the significance of each criterion, AHP was used to calculate the weighting of the GIS layers based on their rating (1, 2, 3, and 4). By combining the rating layers with their weights, a map was created that classified areas of R. N. Macedonia into four categories (highly suitable, suitable, less suitable, or unsuitable) for installing PV power plants. The weights that were assigned to each criterion using the AHP method were determined to be acceptable, as the consistency ratio was below 0.1.

We determined that approximately 2880 km² of the study area (or 11.6%) was highly suitable for PV power plant installation – predominantly in the Vardar and East regions. Utilizing just 0.6% of this land for PV technology could potentially generate an estimated 2870 GWh/year, highlighting the significant contribution to meeting the industrial sector's electricity demands across the administrative regions.

There are ways to improve the analysis process in future work. One limitation of this study was the variation in the data sources. The data sets that were used in this study were collected at different times and had inconsistent resolutions. To improve the accuracy of the model in the future, it would be beneficial to use consistent updated data sets that have consistent times and spatial resolutions. It would also be useful to include economic information about the selected areas in order to identify the most geographically and economically suitable locations. Additionally, field surveys of PV candidate sites will be necessary in order to identify and validate locally important constraints and factor variables from an urban-planning perspective.

The developed suitability map and technical potential evaluation are crucial tools for decision-makers and investors. They support strategic planning for future electricity-generation targets and investment allocation, and they contribute to achieving a 30% reduction in GHG emissions by 2030. This study exemplifies a technical approach that balances environmental sustainability with practical energy needs.

Author Contributions

Vancho Adjiski: writing – original draft, conceptualization, formal analysis, investigation, methodology, software, validation.

Dalibor Serafimovski: writing – review & editing, supervision.

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