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Research Article

A Novel Procedure for the AHP Method for the Site Selection of Solar PV Farms

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This study proposes a novel approach to enhance the analytic hierarchy process (AHP) for the selection of suitable sites for solar photovoltaic (PV) farms. This approach is particularly beneficial when it is possible to establish a predefined objective relation in the final weights of the AHP method. The methodology focuses on achieving this predefined relation introducing a systematic revision of the constants of related constraints. In this study, the costs of constructing a unit transmission line and road in the Kayseri Province are objectively related, and the initial constant matrix of the AHP method is iteratively revised until the relation of the final weights converges to the predefined one. The suitability of solar PV farm locations is classified into five classes, revealing approximately 28% (40-100% of suitability) of the province as favorably suitable and designating about 67% as restricted zones. The findings reveal notable distinctions between the revised weights and those derived from the conventional AHP method. The disparity in weights for various constraints varies from 13.5% to 7.2%. Consequently, the alterations in the area of suitability regions range from 3.4% to 50%. The revision of AHP weights results in a reduction in higher-suitability areas, coupled with a significant expansion in the region exhibiting lower suitability. Notably, the extent of change in the suitability map increases when the difference in ratios between two criteria obtained from the AHP and the predefined objective relation is high. The proposed method demonstrates its applicability in regions like Kayseri where an objective relation between criteria can be established. Given the inherent subjectivity of the AHP method, the proposed procedure becomes essential to attain more objective weights. Since the methodology objectively adjusts weights based on known ratios, it increases the accuracy and reliability of site selection studies.

1. Introduction

Energy is a key factor in the social and economic development of any country. Achieving a sustainable and affordable supply of clean, renewable energy sources is essential to ensure sustainable development [1–5]. Efforts to reduce greenhouse gas emissions, such as the Kyoto Protocol and the Paris Agreement, are aimed at increasing the proportion of renewable energy sources. During the 26th UN Climate Change Conference of the Parties, both the European Union and the USA pledged to reduce their greenhouse gas emissions by 50 percent below 2005 levels by 2030 [6]. Simultaneously, China has committed to boosting its renewable energy sources to constitute 25% of its overall energy supply. Recognizing the severity of global warming as one of the most pressing issues, many countries are actively planning to transition to alternative energy sources to mitigate the adverse effects of climate change. Countries aiming to reduce their greenhouse gas emissions are heavily relying on increasing their energy supply from renewable sources. Solar energy, in particular, has seen a remarkable growth of 3000% between 2010 and 2021 [7, 8]. Many nations are actively working to enhance their solar power capacity by assessing their solar potential [9].

Efforts to improve the efficiency of solar systems often involve selecting optimal locations for solar photovoltaic

(PV) systems. Various multicriteria decision-making (MCDM) methods are employed for this purpose, with the analytic hierarchy process (AHP) standing out as one of the most widely used methods [10]. In AHP, factors influencing the selection of suitable locations for solar PV panels are categorized into criteria groups, and their weights are determined. This process is typically carried out in a geographical information system (GIS) environment to map favorable locations for solar PV panels.

The AHP, integrated with GIS, has been successfully applied for the site selection of solar PV panels. In Granada, Spain, a study [11] utilized AHP to investigate factors such as environment, orography, location, and climate in determining the best sites for solar PV panels. Similarly, in Oman, another study [12] employed ordered weighted averaging along with AHP to identify suitable locations for solar plants, revealing that 0.5% of the study area was highly suitable. Approaching site selection from a different angle, a study in China [13] outlined critical factors for choosing sites for solar-wind hybrid power stations, including accessibility, resources, economics, risks, and environmental attributes, with the aim of improving the usability of evaluation results. In southern Morocco, another study [14] utilized AHP, considering land use, orography, location, and climate as criteria for suitable site selection, emphasizing climate as the key criterion influencing potential electricity production for photovoltaic fields. The most suitable sites were identified as having flat ground oriented towards the south. Eastern Morocco saw a similar application of AHP integrated with GIS for PV site selection [15], with criteria such as climate, orography, location, and water resources. Climate emerged as the most critical factor, aligning with previous findings. Fuzzy AHP was employed in India [16] to assess the spatial suitability of solar farm locations, taking into account technical, economic, and environmental factors, with climate once again identified as the most crucial criterion. Similar studies integrating MCDM with GIS were also conducted for several countries such as Iran [17–20], Tanzania [21], Spain [22, 23], Ethiopia [24], Pakistan [25–27], Tunisia [28], and Saudi Arabia [29].

Türkiye is also an attractive country for the installation of solar PV farms due to its abundant sunlight. According to a modeling study [30], the projected growth of PV capacity in Türkiye suggests that it will constitute 14% of total electricity capacity by 2030 and 29% by 2040. Recognizing the need for effective policies, [31] suggests that incentive measures have been put in place to boost Türkiye's solar energy levels, with legislative amendments governing the use of renewable energy sources.

The surge in interest is evident in the construction of a substantial solar power plant with a capacity of around 1.3 GW in Konya [32], a central region of Turkey. Given the limited available land, identifying the most suitable sites for solar PV panels has become a focal point for researchers. In Konya, for instance, [33] employed the AHP-GIS approach, considering environmental and economic factors to determine suitable site selection for solar farms. Similarly, in the neighboring city of Karaman, [34] conducted a solar PV farm site selection analysis, utilizing AHP as a multiple criteria decision-making (MCDM) method and considering environmental and economic factors. In Kahramanmaraş, Türkiye, [35] proposed a framework based on AHP-GIS for solar PV farm site selection, with geography, climate, and location as the primary criteria. Climate emerged as a crucial factor, aligning with findings from previous studies. In İzmir, Türkiye, [36] introduced a method, combining AHP and an optimality-based site growing approach, to identify the most suitable regions for constructing large-scale PV farms. Notably, land cost was considered as a criterion, distinguishing it from other studies in literature. In Muğla, Türkiye, flood and erosion risks were incorporated into the AHP criteria for assessing their impact on solar PV farm site selection [37]. The GIS-AHP approach was also applied to identify suitable sites for solar PV farms in Malatya [38] and Kayseri [39], Türkiye.

As explained, the AHP has been widely employed for the site selection of solar PV farms. While AHP offers the advantage of utilizing a hierarchical structure to streamline comparisons and reduce their number, a notable drawback is the variability in factors depending on the form of the hierarchy structure [40]. In the process of selecting the most suitable locations for solar PV panels, experts are responsible for determining and comparing the criteria. After assigning priorities to each criterion by establishing a hierarchical importance with expert opinions, AHP is applied to determine the final weights for each criterion. However, because the prioritization among the criteria relies on expert opinions or literature, the final weights of certain criteria may differ from what was initially expected. To achieve predetermined final weights and enhance the objectivity of the AHP method, a modification to the methodology is imperative.

The main aim of the present study is to revise the final weights of the criteria calculated from the AHP method by establishing objective comparisons between two criteria. Specifically, the study is aimed at adjusting the AHP calculations systematically when the quantitative importance ratio of two criteria is known. In essence, if the ratio between the importance of two criteria can be quantified, the AHP calculations are revised to align the ratio of two known values by systematically altering the initial AHP matrix. As an example, in the selection of the suitable locations of solar PV panel, the ratio of the costs associated with distance to transmission lines and distance to roads can be obtained from the literature. Therefore, the ratio of the final weights for these two parameters is known. However, in the AHP process, where comparisons are made between each criterion, the final ratio of the weights for these two parameters may differ significantly from the known ratio. In the present study, a methodology is proposed to determine the accurate ratio of the weights for two parameters by modifying the initial AHP matrix. The method recalculates all the weights for each criterion by considering the known ratio of any two final weights while minimizing changes in weights other than the known ones. To the best of the authors' knowledge, this study represents the first attempt to develop a methodology that modifies the initial matrix, provided by experts, or extracted from the literature, to adjust the final weights considering a known ratio between the weights of two criteria.

The paper is structured as follows: The subsequent section elaborates on the proposed methodology, along with an explanation of site properties and criteria used in the AHP. Following this, the results derived from the suitability analysis are presented and discussed. Additionally, the findings are contextualized in relation to existing wind farms, and a comparative analysis is conducted between the outcomes of the proposed methodology and those obtained through conventional AHP analysis. In the conclusions section, key takeaways are drawn.

2. Methodology

2.1. Revision of AHP Weights. At the very beginning of the AHP method, predetermined interrelationships among constraints are established by experts or through survey results [41]. Experts express their opinions regarding the relationships between each constraint, and consensus among experts may be reached. Despite this consensus, the AHP method iteratively refines, recalculates, and synthesizes these relationships into the weights assigned to each constraint. Ideally, if a relationship is deemed accurate and precise by the experts, it should be faithfully reflected in the AHP results as the weights. However, within the AHP process, even when the exact ratio between any two constraints is known, the ratio of the final weights may deviate from the anticipated value. To ensure the persistence of specific predefined relationships in the AHP results, the authors propose a method that involves modifying the constants within the AHP method.

In the presented methodology, experts articulate their opinions regarding the relationships, as in the conventional AHP method. These relationships are denoted as C_{ini}. It is presumed that the precise relationship between two constraints, denoted as k and l, is either known or objectively determined. This relationship, represented as a ratio α, is expected to align with the final AHP weights calculated for these constraints.

$$C_{\text{ini}} = \begin{bmatrix} 1 & a_{1j} & \cdots & a_{1n} \\ a_{i1} & 1 & \cdots & a_{\text{in}} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{\text{nj}} & \cdots & 1 \end{bmatrix}, \quad W_{\text{ini}} = \begin{bmatrix} w_1 \\ w_i \\ \vdots \\ w_n \end{bmatrix}. \tag{1}$$

In equation (1), C_{ini} is the initial comparison matrix determined by the experts and W_{ini} is the corresponding weights calculated using the conventional AHP method where n is the number of constraints. The constants a_{ij} are optimized based on the final known relations between two constraints. Only the rows and columns including the constants of related constraints undergo optimizations.

The optimization procedure initiates with the incrementation of relation constants, a_{ij}. After applying an increment, δ, to a relation constant $a_{\text{ij}} = a_{\text{ij}} + \delta$, the change in final weights, $\Delta W_H{}^{\text{ij}}$, is calculated by

$$\Delta W_H{}^{\text{ij}} = \text{abs}\left(W_H{}^{ij} - W_{\text{ini}}\right), \tag{2}$$

where $(j = k \text{ for } i = 1, k-1)$ and $(j = l \text{ for } i = 1, l-1)$ and $(i = k \text{ for } j = k+1, n)$ and $(i = l \text{ for } j = l+1, n)$ and $W_H{}^{\text{ij}}$ is the corresponding weights for C_H matrix of which a_{ij} constant is incremented.

The maximum change in final weights, max $(\Delta W_H{}^{\text{ij}})$, specifies the optimal deviating constant. Incrementation should be applied $2 * (n-1) - 1$ times the number of constants for one pair of relations. The optimal deviating constant is the most effective one, causing a more substantial change in final weights compared to other constants. Therefore, revising this optimal deviating constant by an amount of increment, δ, enhances the AHP solution. As a result, the relationship between α_{new} (calculated by equation (3)) converges to the predefined relationship α.

$$\alpha_{\text{new}} = \frac{W_H(k)}{W_H(l)}. \tag{3}$$

A singular cycle of incrementation is insufficient for nonlinear optimizations. Therefore, this procedure is iteratively repeated until the final relations of k and l are equal to the predefined constant α. The outlined procedure is explained in the flowchart given in Figure 1.

2.2. Site Properties. Kayseri, situated approximately at the geographic center of Turkey, is positioned near the Taurus Mountains on the Alpide belt, resulting in predominantly mountainous terrain. The expansive Erciyes Mountain, covering a region of 3300 km^2 within the Kayseri Province, accounts for about 20% of the city, encompassing an area of 17000 km^2 [42]. With an elevation of 3917 m, Erciyes Mountain ranks as the sixth-highest mountain in Türkiye. Additionally, the peak of Kızılkaya mountain (3771 m), the ninth-highest mountain in Turkey, is located within the boundaries of Kayseri, specifically in the southern region designated as the Alacadağ National Park. Although Kayseri has the roofs of Türkiye, the remaining parts of the terrain have mild sloped hills except the Sultan Reed which is the widest (1000 km^2) flat region of Kayseri. The Sultan Reed is situated on the northwest foothills of Erciyes Mountain, with a portion of the area reserved for wildlife.

The primary settlement in Kayseri is positioned at the northern foothills of Erciyes Mountain. Kayseri shares its borders with Yozgat and Sivas to the north, Kahramanmaraş to the east, and Adana and Niğde to the west. The main transportation routes connect the city to neighboring cities such as Nevşehir, Niğde, and Sivas, while direct routes to Kahramanmaraş and Adana are hindered by the Taurus Mountains. The geographic location of Kayseri, along with the digital elevation model (DEM), is illustrated in Figure 2. The study employs the Copernicus DEM, which has a

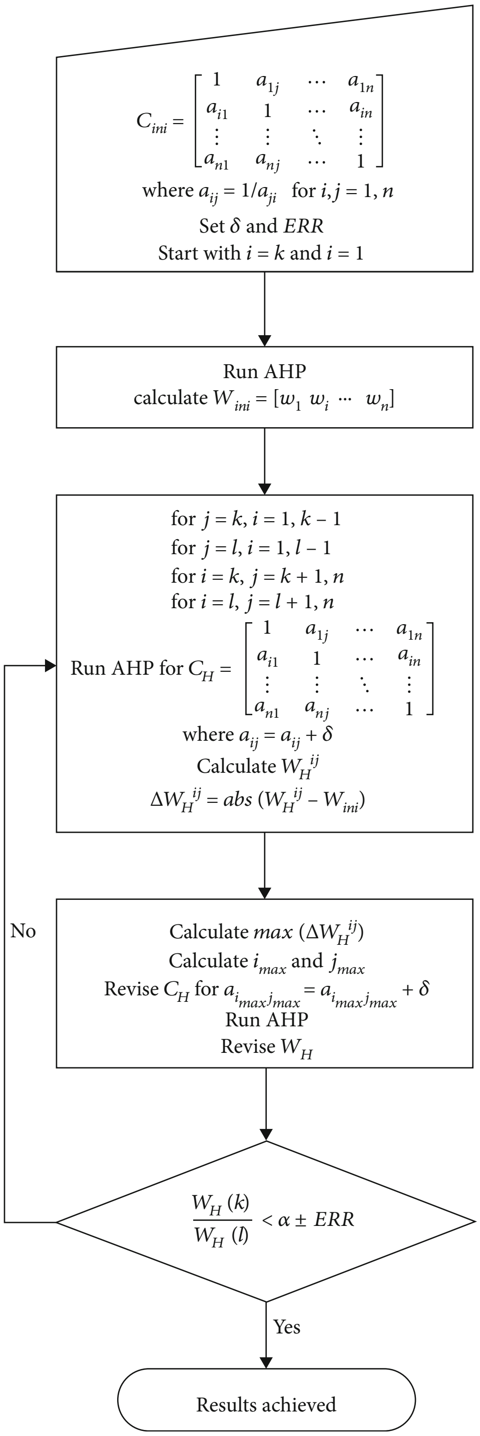


Figure 1: The flowchart for revision of AHP weights.

25-meter resolution and is derived from data collected during the TanDEM-X mission conducted between 2011 and 2015 [43].

2.3. The Criteria List. Six criteria are considered for the assessment of the Kayseri Province: solar radiation rate, land use, slope, distance to transmission line, road, and residential area. The inclusion of the solar radiation rate is warranted due to the extensive and nonuniform solar energy distribution across the province. Land use is also taken as a criterion, considering the importance of the lands of a deserted world. Given that Kayseri is characterized by mountainous terrain, the slope is integrated into the AHP calculations to account for the topographical features. Additionally, distance to transmission lines, roads, and residential areas are included as constraints with cost implications. These constraints play a pivotal role in the spatial site selection of solar farms, directly impacting both the initial and maintenance costs associated with the projects.

2.3.1. The Solar Radiation Rate. The solar radiation rate in the Kayseri Province exhibits a range from 1550 to 1800, as depicted in Figure 3(a) [44]. The highest rate is situated in the southwest of the Erciyes foothills, particularly in a wide, flat region proximate to the Sultan Reed. Conversely, the lowest rate is observed near Aladağlar National Park, located to the south of Kayseri. Notably, the peak of Erciyes Mountain demonstrates a lower solar energy yield. Owing to this variability in solar radiation, it is included as a constraint in the AHP calculations, aligning with precedents set in earlier studies [11, 15, 45].

2.3.2. Land Use. Figure 3(b) displays the land use distribution in Kayseri. The land use classes are delineated using Sentinel-2 Satellite imagery, providing an approximate resolution of 10 meters. The time series for global land cover spans from 2017 to 2021. Predominantly, the province is covered by rangelands, constituting the primary land use class. Crops cover approximately 15% of the province, and despite the presence of the longest river in Türkiye, Kızılırmak, in the northwest, cultivation and forest regions are limited. Forests, covering only 4% of the province, are predominantly located on the Toros Mountains, forming the southeastern border of Kayseri. Moreover, there is a flooded vegetation area that serves as a source of income for some locals. Despite its economic value, and considering the polluted, populated, and deserted world, cultivation areas are designated as restricted areas. Consequently, only bare ground and rangeland are permissible locations for the placement of solar farms, in line with previous studies [20, 21, 45–47].

2.3.3. Slope. The Kayseri Province features some flat regions, but the majority of the area is characterized by mountainous terrain. The entire southeast border of Kayseri constitutes a mountainous region known as the Toros Mountains. Additionally, Erciyes Mountain covers approximately 20% of the city [42]. A notable flat region on the southeast foothills of Erciyes Mountain is called Sultan Reed. Although this region has a very mild slope (<3%), making it highly suitable for construction, it is noteworthy that almost one-third of this flat area is designated as a national park. Other parts of Kayseri also contain partially flat regions, but these are not as flat as Sultan Reed.

The slope distribution of Kayseri is derived from the DEM using the least square method, as illustrated in Figure 3(c). Notably, regardless of the terrain's aspect, terrains with mild slopes exhibit the same sunny hours. Given this uniformity in solar panel orientation, only a minor

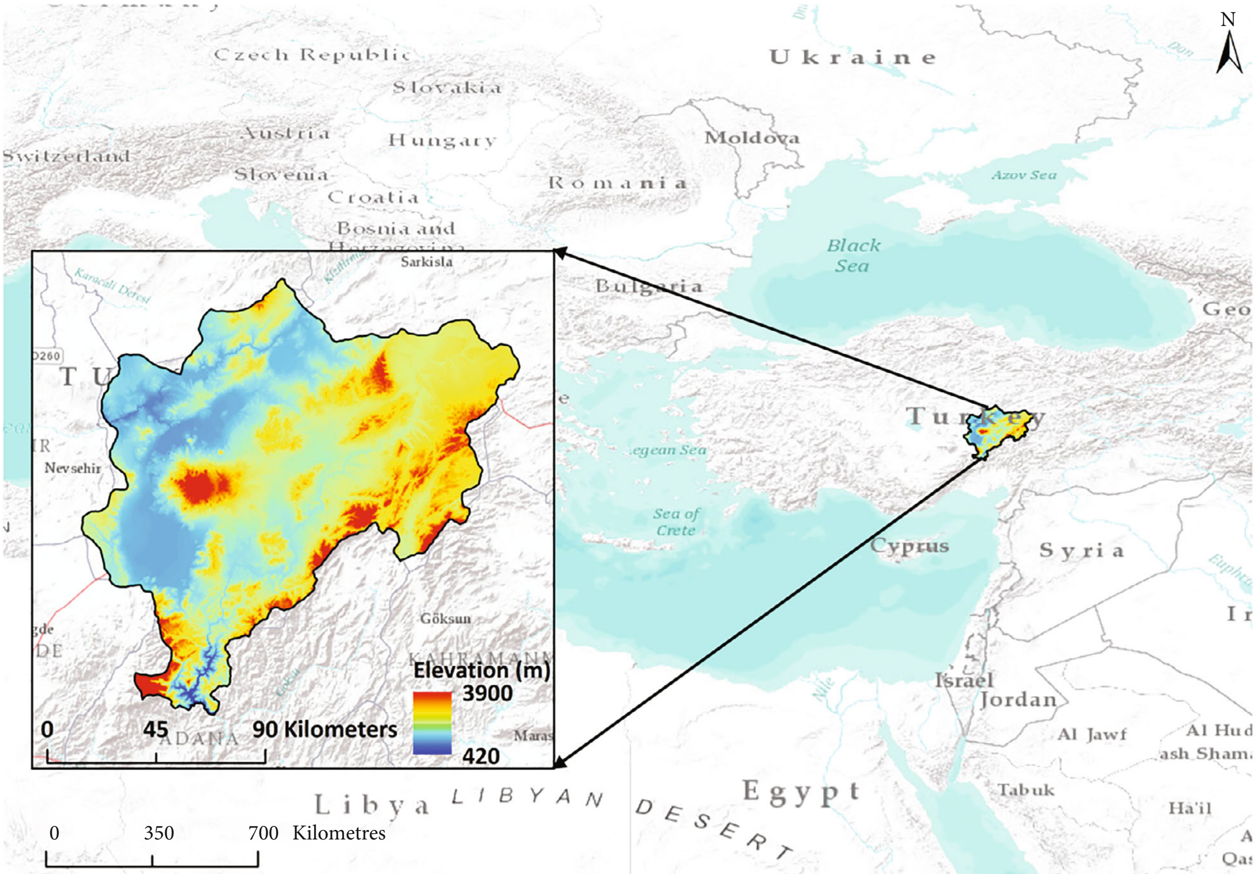


Figure 2: The location and DEM of Kayseri.

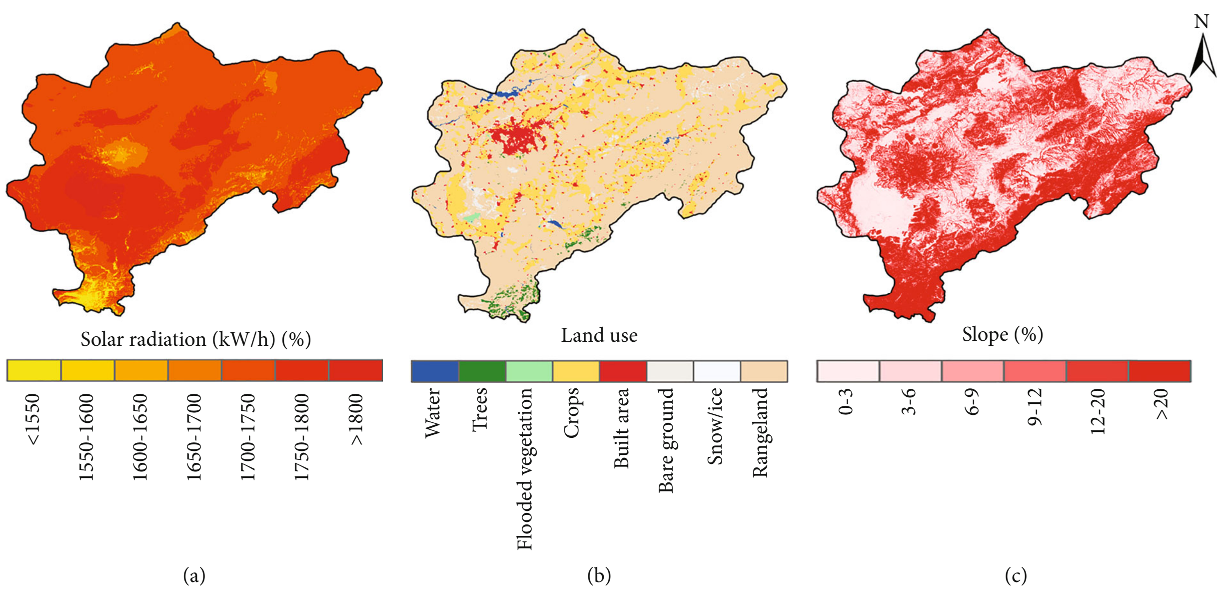
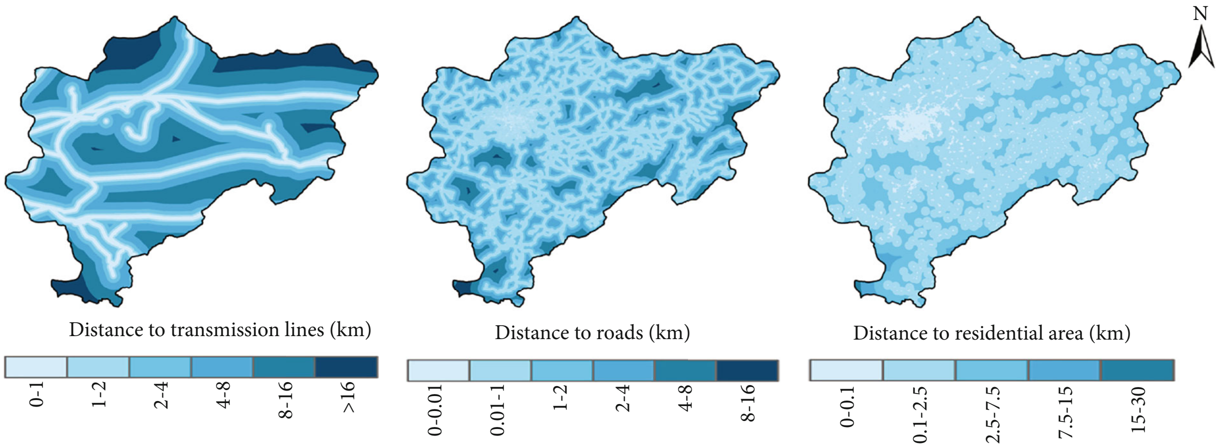


Figure 3: Solar radiation, land use, and slope maps of Kayseri.

difference is observed in the construction aspect for these terrains. Consequently, the aspect is considered inconsequential for terrains with mild slopes in Kayseri. Therefore, for the Kayseri Province, the aspect is disregarded, and steep slopes (>20%) are restricted for solar farm construction.



(a) (b) (c)

FIGURE 4: Distance to transmission line, road, and residential area maps of Kayseri.

TABLE 1: The criteria and subcriteria list and the related weights.

Criterion	Weight	Subcriteria	Indicators	Criteria	Weight	Subcriteria	Indicators
Solar radiation rate	36.92	<1550	3	Slope (%)	10.44	0-3	9
		1550-1600	4			3-6	8
		1600-1650	5			6-9	7
		1650-1700	6			9-12	4
		1700-1750	7			12-20	2
		1750-1800	8			>20	Restrained
		>1800	9				
Land use	23.63	Water	Restrained	Distance to road (km)	6.08	0-0.01	Restrained
		Trees	Restrained			0-1	9
		Flooded veg.	Restrained			1-2	8
		Crops	Restrained			2-4	7
		Built area	Restrained			4-8	6
		Bare ground	8			8-16	4
		Snow/ice	Restrained			>16	2
		Rangeland	9				
Distance to transmission line (km)	18.21	0-1	9	Distance to residential area (km)	4.72	0-0.1	Restrained
		1-2	8			0.1-2.5	9
		2-4	7			2.5-7.5	7
		4-8	6			7.5-15	5
		8-16	4			15-30	3
		>16	2			>30	1

2.3.4. Distance to Transmission Lines. The significance of the distance to transmission lines is particularly pronounced in developing countries. This is due to the fact that the rural population in developing countries may lack access to electricity [48]. However, it is worth noting that Türkiye does not share this issue, as its extensive network of transmission lines effectively covers almost the entire province. With the exception of regions near the northern border, the longest distance to the nearest transmission line in any part of the province is 16 km, as depicted in Figure 4(a). The indicators utilized in this study, as presented in Figure 4(a) and Table 1, are determined based on existing literature [49, 50], wherein a closer distance to transmission lines indicates a more favorable site for power plants. It is essential to underscore that the influence of different types of transmission lines on distance requirements is not considered in any prior site selection studies, including the present one. Furthermore, it is noteworthy that despite the heightened risk perceptions among residents in close proximity to high-voltage transmission lines, as documented in [51], a buffer zone is not employed. This decision is attributed to the fact that the large solar power plants examined in this study are not situated in close proximity to residential areas, as elucidated in Section 2.3.6.

The Euclidean distance to the transmission lines is calculated using data from OpenStreetMap [52]. The greater the distance to the transmission lines, the higher the construction cost of the solar farm. Therefore, the distance serves

Table 2: The initial comparison matrix.

	Solar radiation rate	Land use	Distance to transmission line	Slope	Distance to road	Distance to residential area
Solar radiation rate	1	2	3	4	5	6
Land use	0.5	1	2	3	4	5
Dist. to trans. line	0.333	0.5	1	2	3	4
Slope	0.25	0.333	0.5	1	2	3
Dist. to road	0.2	0.25	0.333	0.5	1	2
Dist. to res. area	0.167	0.2	0.25	0.333	0.5	1

Table 3: Revised comparison matrix.

	Solar radiation rate	Land use	Distance to transmission line	Slope	Distance to road	Distance to residential area
Solar radiation rate	1	2	2.276	4	5	6
Land use	0.5	1	1.276	3	4	5
Dist. to trans. line	0.439	0.784	1	2	3	4
Slope	0.25	0.333	0.5	1	2	3
Dist. to road	0.2	0.25	0.333	0.5	1	1.276
Dist. to res. area	0.167	0.2	0.25	0.333	0.784	1

as a cost-related criterion. This implies that this constraint can be correlated with another criterion, also based on cost considerations. The relationship between cost-related constraints is elaborated in Section 2.4.

2.3.5. Distance to Road. This criterion pertains to the construction cost of a road from the chosen site to the nearest existing road. Consequently, similar to the distance to transmission lines, this criterion is also cost-related. The maximum distance to the nearest road from any part of the province is approximately 16 km, as illustrated in Figure 4(b). The calculation of the distance to the road involves the use of Euclidean distances utilizing data from OpenStreetMap [52]. While having a site in close proximity to a road is advantageous, a buffer zone of 10 m from the edge of the lane is chosen to account for the lanes of the road [22, 32, 33, 45].

2.3.6. Distance to Residential Area. The criterion of distance to the residential area is primarily defined to account for the operational costs of the solar farm, impacting both operational and maintenance expenses. The close proximity to the residential reduces transportation costs for materials, equipment, and personnel, contributing to overall cost efficiency [35, 37]. The shorter distance may also result in minimized transmission losses, optimizing the effectiveness of energy delivery, and potentially reducing operational expenses [20, 53]. Furthermore, the advantage of quicker emergency response times in close proximity can lead to cost savings by minimizing potential damage and associated recovery costs. The impact of increased distance from residential areas on additional costs exhibits a notable disparity between large-scale and small-scale solar farms. This discrepancy arises from the substantial initial investment associated with large-scale solar power plants in contrast to their relatively lower maintenance and operational costs. Studies focused on the site selection of large-scale solar farms have typically omitted the distance to residential areas as a significant criterion, emphasizing the limited influence of such considerations on the economic viability of large-scale solar farm installations [36].

Considering that existing solar farms are generally small in scale (maximum 50 MW), this criterion is considered in AHP calculations for Kayseri, consistent with prior studies [16, 17]. The distance to the residential area is computed based on the land cover information extracted from Sentinel-2 Satellite imagery.

The subcriteria for the distance to the residential area are defined with consideration for the mobility of an employee. The distance to the nearest residential area is subdivided into six categories. The first category includes distances up to 100 m, where the solar farm is considered to be within the city and is thus treated as a buffer zone. The second category comprises distances up to 2.5 km, a comfortable walking distance. The third category represents a comfortable biking distance of 7.5 km. The fourth category considers a comfortable motorbike distance of up to 15 km. The fifth category encompasses distances up to 30 km, suitable for travel by car. The final category is defined as greater than 30 km, indicating a need for on-site residential facilities for farms situated at such distances from existing residential areas. However, in Kayseri, there is no location falling under the sixth criterion, as illustrated in Figure 4(c).

2.3.7. Restricted Areas. Restricted areas encompass more than half of the Kayseri Province and include national parks, cemeteries, military zones, historical sites, reservoirs, forests, flooded vegetation basins, cultivation regions, built-up areas, regions covered by snow or ice, terrains with slopes greater than 20%, and areas in close proximity to roads.

2.4. Revision of the AHP Weights Based on the Objective Relation of Constraints. The AHP serves as a MCDM method, condensing cross-relations between constraints and determining the weights of each constraint. In the present study, the cross-relations are determined by the faculty

Table 4: Original and revised weights achieved by AHP analysis.

	Solar radiation rate	Land use	Distance to transmission line	Slope	Distance to road	Distance to residential area
Revised weights	0.3692	0.2363	0.1821	0.1044	0.0608	0.0472
Original weights	0.3794	0.2488	0.1604	0.1024	0.0655	0.0434
Difference	2.7%	5%	-13.5%	-2%	7.2	-8.8%

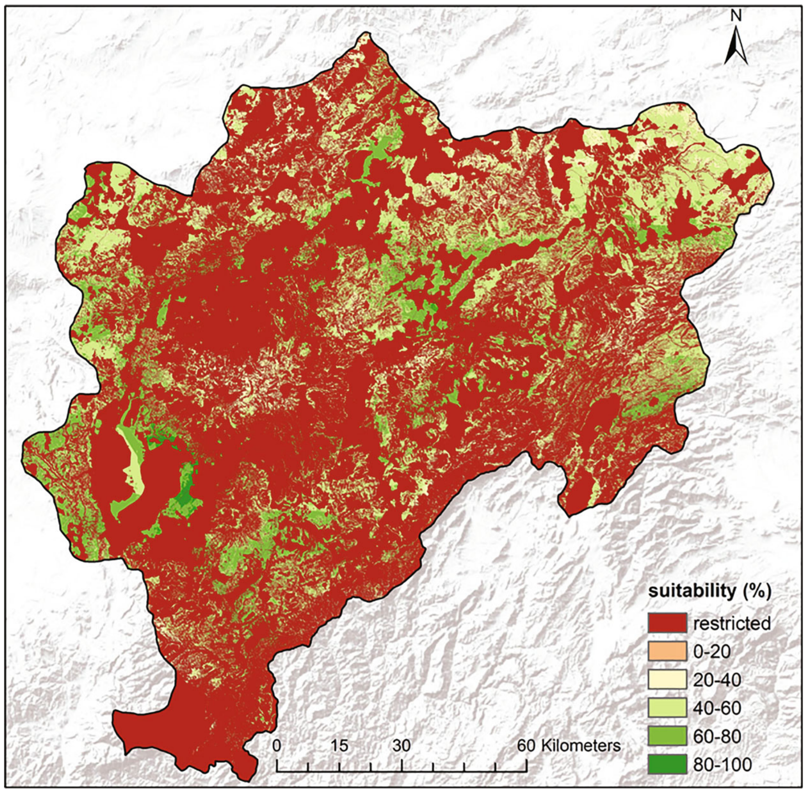


Figure 5: Suitability map of solar PV farms for Kayseri Province.

members from the departments of civil and environmental engineering in different universities in Türkiye. In addition to their input, data from relevant literature sources are also considered, and the initial comparison matrix presented in Table 2 is obtained. These cross-relations, defined by experts, may be either objective or subjective. While subjective relations do not inherently render AHP calculations unreliable, objective relations should be upheld in the final weights of the related constraints. In this context, the comparison matrix is revised based on the predefined relations, with the revision process detailed in the flowchart provided in Figure 1.

The predefined relation should be calculable or based on objective facts. For instance, distance to transmission lines and roads are cost-related constraints, allowing their relationship to be established by calculating costs. In the case of Kayseri Province, the cost of constructing one kilometer of road is one-third of the cost of a transmission line [54]. This ratio must be satisfied in the final calculated weights of the AHP method.

The initial comparison matrix given in Table 2 is revised and resulted in a new comparison matrix presented in Table 3. The predefined ratio is indeed satisfied in the final weights, as depicted in Table 4, which are calculated from the new matrix.

Table 5: Area covered by suitability classes.

Suitability (%)	Area (km^2)	Area (%)
Restricted	11440	67.13
0-20	4	0.02
20-40	742	4.35
40-60	3342	19.61
60-80	1471	8.63
80-100	44	0.26

In the raw matrix, only the constants corresponding to the related constraints can be altered, specifically those in columns 3 and 5, as well as rows 3 and 5. This preserves the expressed opinions about the remaining constraints. Consequently, only the matrix elements (1, 3), (1, 5), (2, 3), (2, 5), (3, 4), (3, 5), (3, 6), (4, 5), and (5, 6) can be revised to accommodate the defined relation between the

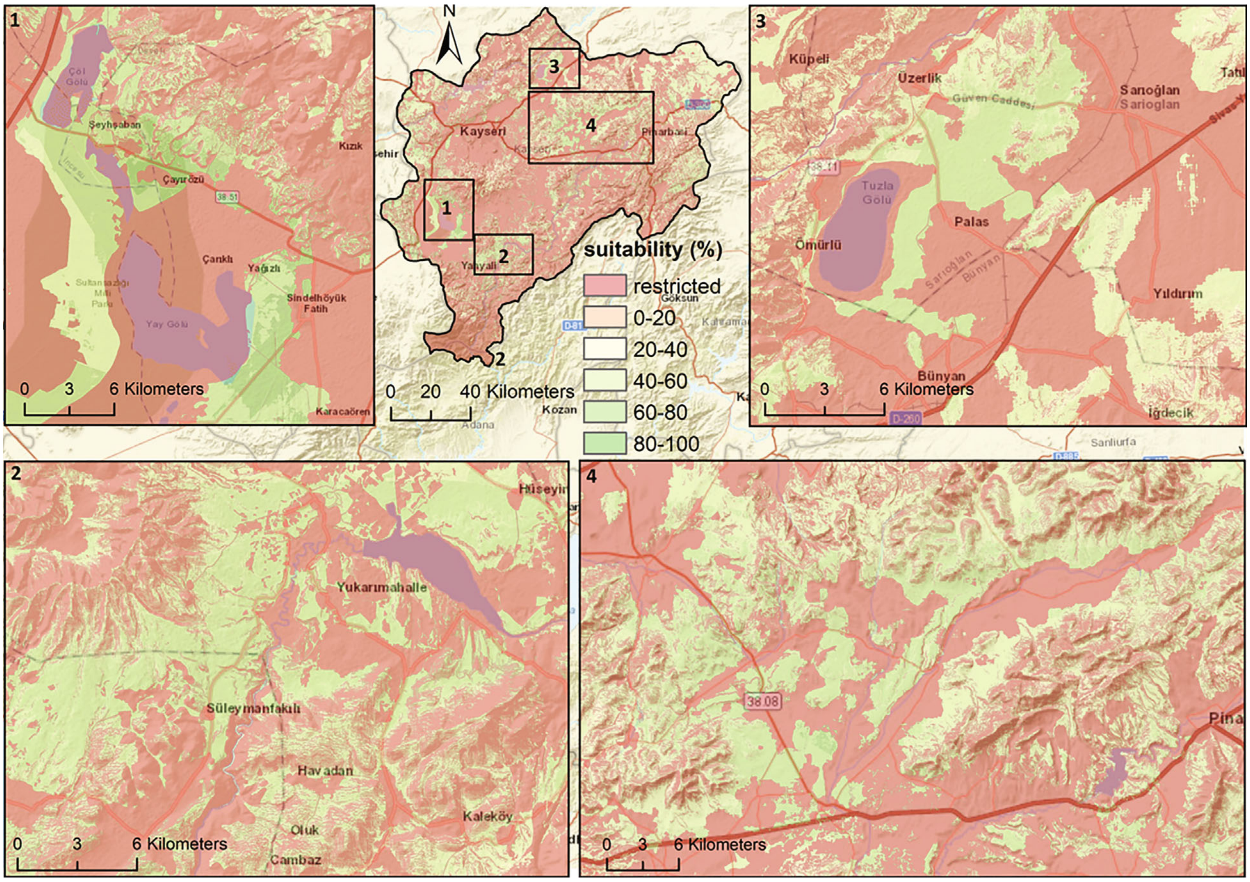


Figure 6: A focused view of the suitable regions for solar PV farms in Kayseri.

distance to transmission line and road. Following the optimal revision procedure outlined in Section 2.1, only the matrix elements (1, 3), (2, 3), and (5, 6) are revised, as illustrated in Table 3. This implies that the relationships between solar radiation rate with the distance to transmission line, land use with the distance to transmission line, and distance to road with the distance to residential area are revised. These are optimal constants to be revised to satisfy the predefined relation (ratio) between distance to transmission line and road.

The relation (ratio) between the distance to transmission line and road that is calculated by the conventional AHP method is 2.45. In contrast, it is adjusted to 3 in the revised AHP weights, as illustrated in Table 4. Notably, revising only three of the constants manifested by experts is sufficient to satisfy the predefined ratio. This revision preserves the hierarchy and does not compromise the overall structure. However, it is important to highlight that while the weights of three constraints (solar radiation rate, land use, and distance to road) decrease, the weights of the other three (distance to transmission line, slope, and distance to residential area) increase as a consequence of this adjustment.

Ultimately, the revised criteria weights, along with the subcriteria outlined in the preceding section, are presented in Table 1. The subcriteria indicators employed in the study align with those commonly found in the literature.

3. Results

The site suitability is categorized into five groups based on percentages: the most suitable (80-100%), suitable (60-80%), moderately suitable (40-60%), relatively suitable (20-40%), and the least suitable (0-20%). Figure 5 visually represents the site suitability, progressing from red to green, with dark green indicating the most suitable sites for solar farms. These highly suitable regions encompass approximately 0.26% of the Kayseri Province. Additionally, areas deemed suitable (60-80% suitability) cover 8.63% of the entire region within the boundaries of Kayseri. In contrast, nearly 67.13% of the Kayseri Province is deemed unsuitable for solar farm development. The specific area covered by each suitability index is detailed in Table 5.

In Figure 6, attention is directed towards four specific suitable areas. In Figure 6 (1), the southwest of Kayseri city center is highlighted, and the most suitable area is identified on the east side of Sultan Reed National Park. The terrain between Çöl Lake and Sultan Reed National Park also emerges as a promising candidate for the installation of solar PV panels. Figure 6 (2) showcases the suitable regions in the south of Kayseri city center. According to the figure, the area encompassed by Yukarımahalle to the west and Süleymanfakılı to the southwest is deemed suitable for the construction of solar PV farms. In Figure 6 (3), attention is focused on the northeast of Kayseri City Center. Potential sites for solar PV

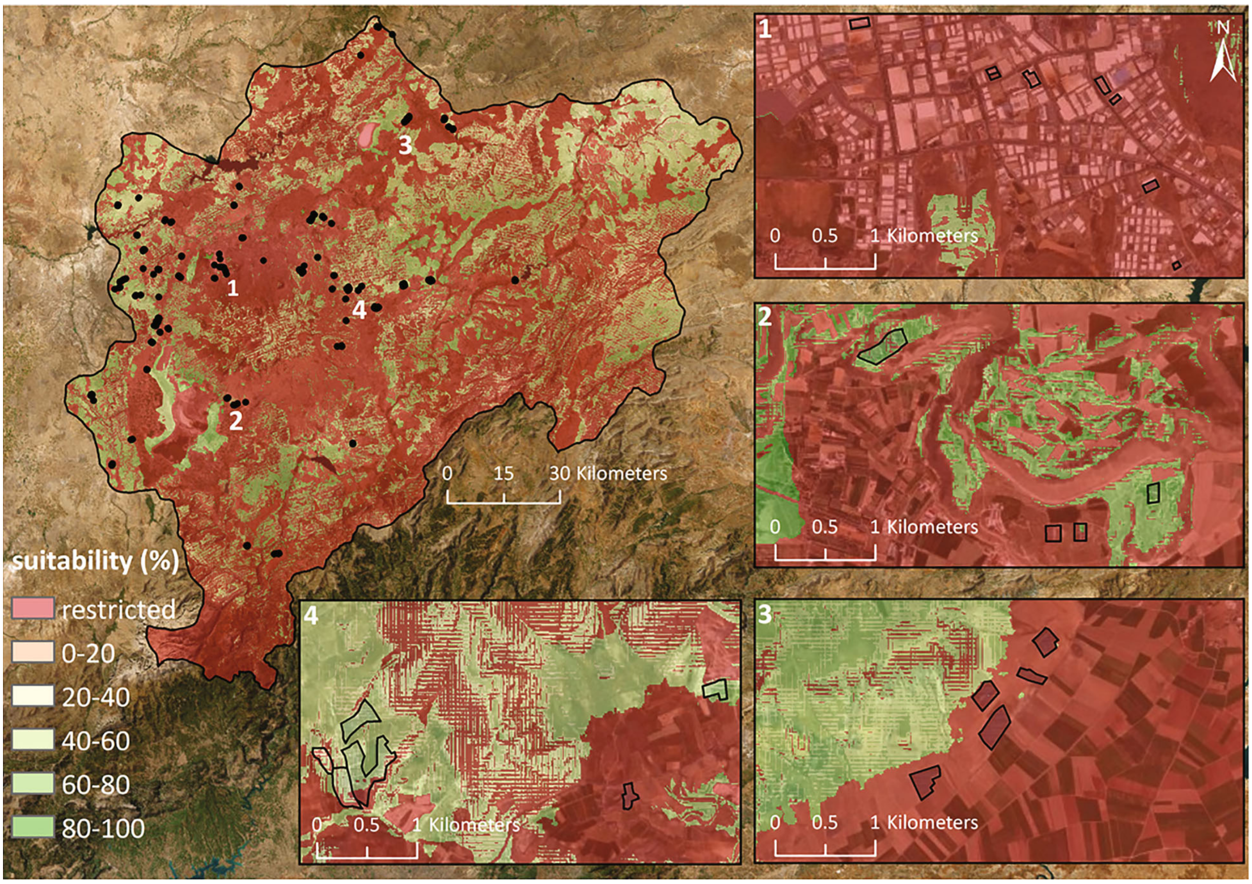


Figure 7: Existing PV farms in Kayseri.

farms are identified in the region bordered by Tuzla Lake, Palas, Sarıoğlan, and Üzerlik. Finally, Figure 6 (4) zooms in on the east side of Kayseri City Center, revealing suitable regions on the west side of Pınarbaşı, as depicted in the figure.

4. Discussion of Results

4.1. Comparison with Existing Solar PV Panels. In Kayseri, a total of 148 solar PV farms are present, with the majority situated on the western side of the province. The farm boasting the highest capacity, with 50 MW, is located in the city's industrial site. Roof-type solar farms are prevalent in Kayseri, with 30 PV farms installed on the roofs of various structures, primarily industrial buildings. Specifically, Figure 7 (1) highlights 8 such farms in the industrial site on the west side of the city center.

Figure 7 (2) provides an overview of the south of Erciyes Mountain, adjacent to Sultan Reed, which encompasses highly suitable regions for solar PV farm construction. Despite the favorable conditions, only 5 existing PV farms are present in this region, with four of them emphasized in Figure 7 (2). Furthermore, the left side, not visible in the zoomed-in figure, is particularly suitable for solar PV farms.

Figure 7 (3) illustrates the establishment of a solar PV farm on cultivation regions in Kayseri. Apart from farms on cultivation regions and roofs, the majority of existing PV farms are situated on sites determined to be suitable by the proposed method. Examples of such farms can be observed in both Figure 7 (2) and Figure 7 (4).

It is important to emphasize that in enhancing the site selection process, it is prudent to refine the chosen locations by incorporating natural hazard assessments. This can be achieved through the application of numerical methods [55–57], which specifically focus on seismic activities. Additionally, considerations should extend to factors such as erosion and flood risks [37], as well as potential landslides and debris flows [58]. Moreover, to address environmental concerns, it is advisable to factor in carbon emissions [8, 59] during the site evaluation process.

4.2. Comparison between the Revised and Conventional AHP Weights. Table 4 provides the weights obtained through both the conventional AHP method and the revised AHP weights. The discrepancies between these weights range from 13.5% to 7.2%, with the maximum absolute change observed in the weight for distance to the transmission line and the minimum absolute change in the weight for slope. Consequently, there is a slight alteration in the suitability map.

To illustrate this change, two regions in the Kayseri Province, both located at the geometric center and to the east of the city center, are selected as shown in Figure 8. The first region, depicted in Figure 8 (1), encompasses four existing PV farms, while the second region, shown in

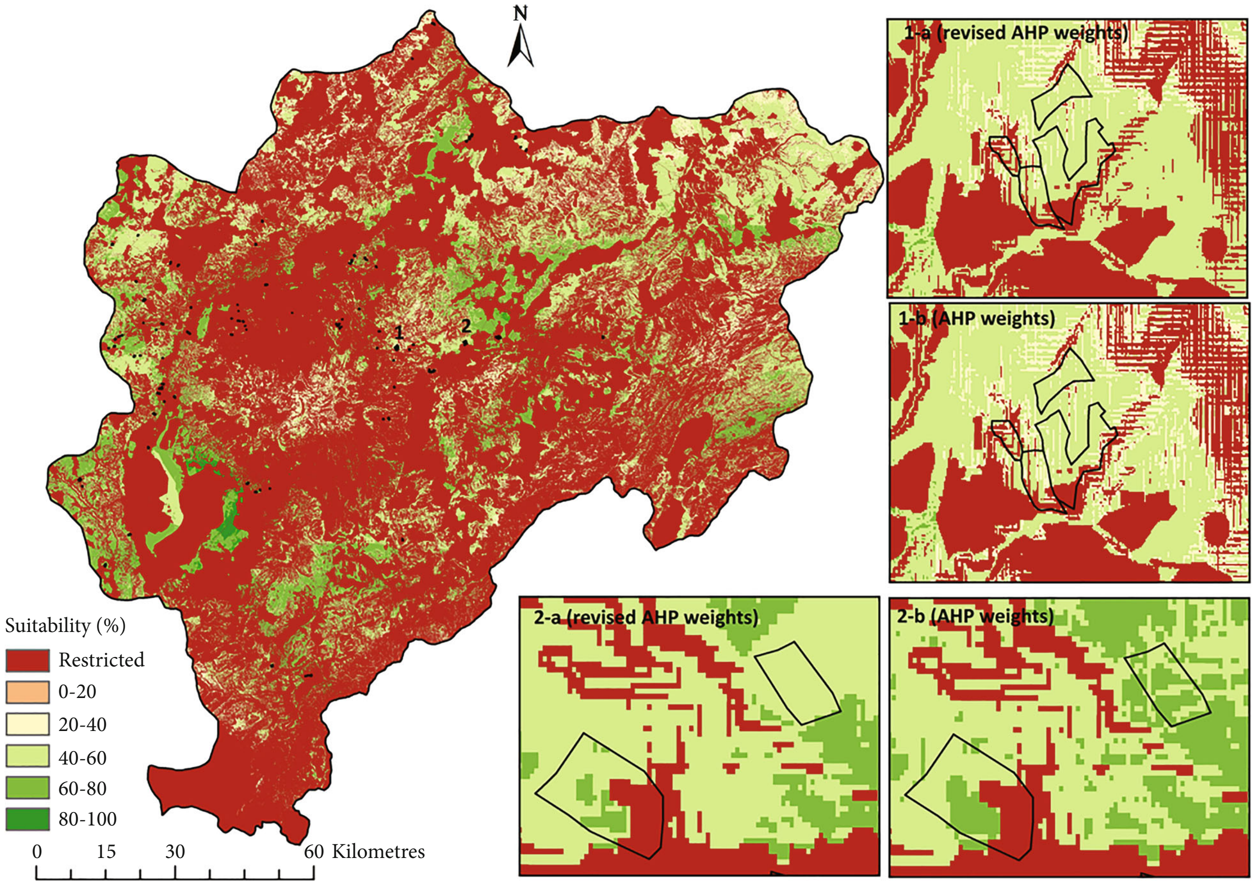


Figure 8: Comparison of revised and conventional AHP weights for some existing PV farms.

Figure 8 (2), contains two existing PV farms. The suitability map generated by the revised AHP weights for the first region is categorized as more suitable compared to the one achieved by the conventional AHP weights. Conversely, for the second region, the suitability map obtained with the revised AHP weights is classified as less suitable than the one achieved with the conventional AHP weights.

The suitability map exhibits a subtle yet noticeable change, as illustrated in Figure 8, upon exiting photovoltaic (PV) farms. Table 6 provides a comparison between the areas identified using revised and conventional AHP. As observed in the table, adjusting the AHP weights results in a decrease in higher-suitability areas, coupled with a significant expansion in the region displaying 20-40% suitability.

The reason for this slight change is discussed by comparing the suitability maps on constraint maps. Accordingly, the most suitable (80-100%) and suitable (60-80%) regions are shown on the maps of distance to transmission line and residential area as seen in Figure 9. A region is focused on that figure and given in Figure 10 to demonstrate the reason of the difference, clearly.

Figure 10 displays the suitability maps for focused regions achieved by both the conventional and revised AHP weights (refer to Figure 9 for the focused regions). Specifically, distance to transmission line and distance to residential area are emphasized for these regions, as revisions in the proposed method predominantly impact the weights of these constraints, as indicated in Table 4. The greatest changes in weights are observed in distance to transmission line and residential area, making these constraints the likely reasons for changes in the suitability map for the entire province.

Table 6: The comparison between the areas determined from revised and conventional AHP weights.

Suitability (%)	Area (%) (revised AHP)	Area (%) (conventional AHP)	Absolute difference (%)
Restricted	67.13	67.13	0
0-20	0.02	0.01	50
20-40	4.35	3.33	23.4
40-60	19.61	20.33	3.7
60-80	8.63	8.93	3.4
80-100	0.26	0.28	7.7

Panels (a), (b), (e), and (f) of Figure 10 are generated using the revised AHP weights, while panels (c), (d), (g), and (h) are generated using the conventional AHP weights. Distance to transmission line serves as the base map for Figures 10(a)–10(d), while distance to residential area serves as the base map for Figures 10(e)–10(h). The most suitable regions (80-100%) are depicted in Figures 10(a), 10(c),

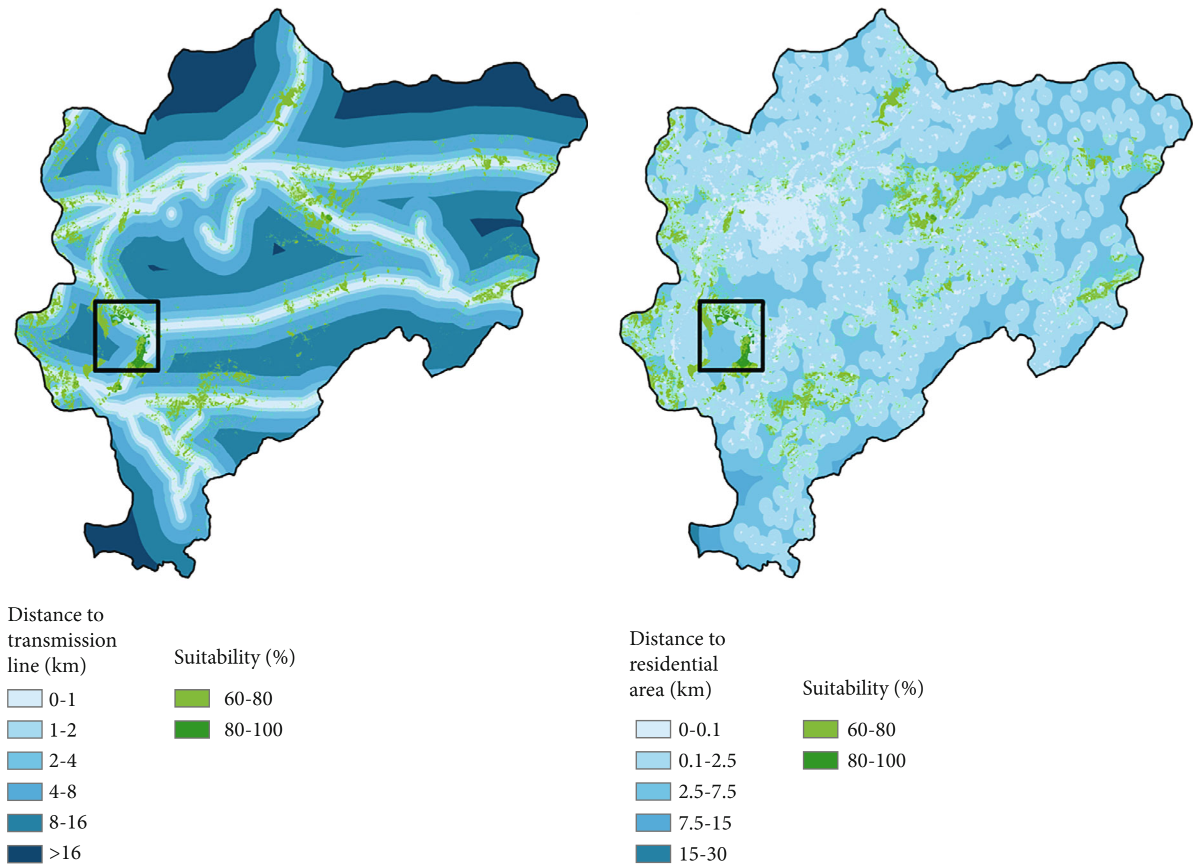


Figure 9: Comparison of revised and conventional AHP weights based on the distance to transmission line (a) and residential area (b).

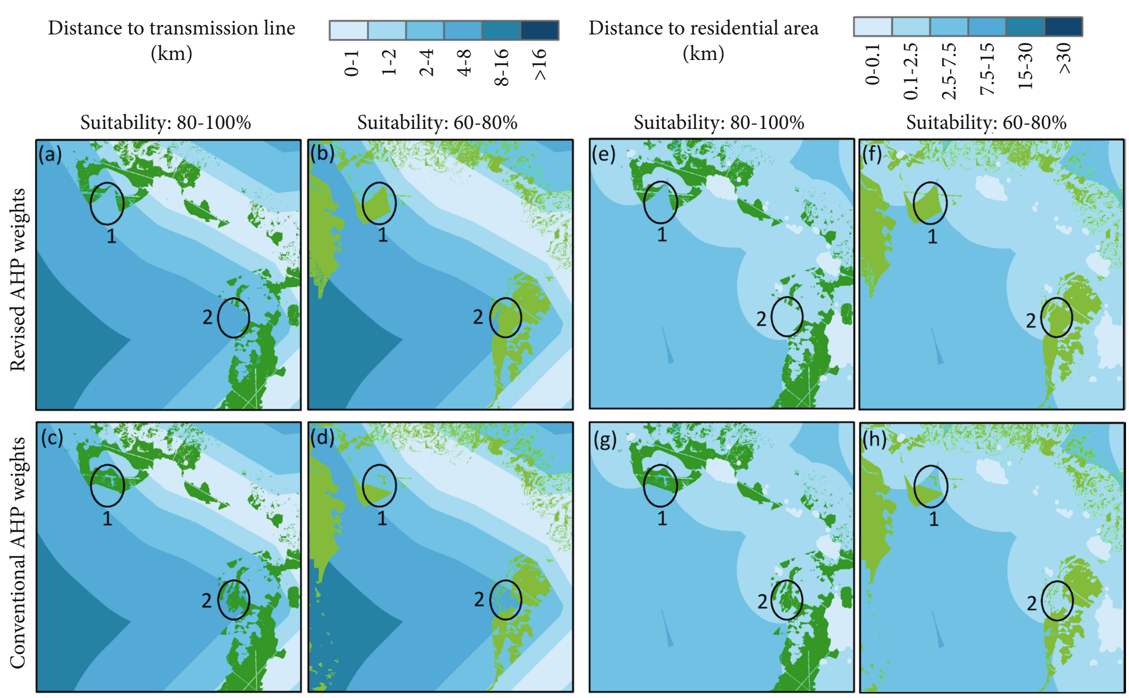


Figure 10: Comparison of revised (a, b, e, f) and conventional (c, d, g, h) AHP weights based on the distance to transmission line (a–d) and residential area (e–h) for most suitable (a, c, e, g) and suitable (b, d, f, h) classes (dark green indicates a suitability range of 80-100%, while light green represents a suitability range of 60-80%).

10(e), and 10(g), whereas suitable regions (60-80%) are shown in Figures 10(b), 10(d), 10(f), and 10(h). The variations between the suitability maps obtained by the revised AHP weights and the conventional AHP weights are highlighted in numbered regions, with the reasons for these differences easily discernible in the figures.

The reason for the disparity in the second region, between the most suitable (80-100%) and suitable (60-80%) cases, is attributed to distance to transmission line (compare Figure 10 (a) with (c) and (b) with (d)). Conversely, the reason for the difference in the first region, between the most suitable (80-100%) and suitable (60-80%) cases, is linked to distance to residential area (compare Figure 10 (e) with (g) and (f) with (h)). The revision of weights results in the reclassification of both regions, downgrading them from the most suitable (80-100%) class to the suitable (60-80%) class.

It is worth noting that [39] utilized conventional AHP to evaluate appropriate locations for solar PV farms in the same study area in Kayseri. A key distinction between our findings and those of [39] lies in the proportion of restricted zones. While [39] identified only 9.43% of the area as restricted zones, our study indicates that this ratio is significantly higher at 67.1%. Additionally, in [39], the ratio of distance to transmission lines to distance to roads was determined to be approximately 2.1. In our study, however, we predefined this ratio as a known value of 3 and recalculated other ratios accordingly. Despite these differences, the most suitable sites for solar PV farms in both our study and [39] are quite similar except for the regions falling into the restricted zones.

4.3. Final Insights on the Methodology. The proposed methodology presents several advantages in enhancing the reliability and objectivity of AHP results. Firstly, it introduces an objective approach to revising AHP weights by systematically comparing criteria, thereby addressing the need for objective comparisons. This method adapts efficiently to situations where the quantitative importance ratio between two criteria is known, aligning AHP calculations with predefined relations obtained from literature or expert opinions. Additionally, by minimizing changes in weights other than the known ratios, the methodology ensures that adjustments maintain the overall consistency of the AHP model.

However, the proposed methodology is not without its challenges. One notable disadvantage is its sensitivity to the accuracy of initial conditions provided by experts or literature. The reliability of the final weights is contingent on the precision of these initial conditions. However, this concern may not be significant, as the ratios derived from the initial AHP matrix, obtained from experts or literature, are not anticipated to deviate significantly from the known ratios. In the current study, for instance, the calculated and known ratios for the two criteria are 2.44 and 3, respectively, and the proposed methodology functions smoothly without any issues. Moreover, the iterative optimization cycles required by the methodology may pose challenges, particularly in cases where nonlinear optimizations are necessary. This could increase computational complexity and time requirements. The limitations of the methodology stem from its dependency on known ratios between specific criteria. In situations where such ratios are unavailable or inaccurate, the applicability of the proposed method may be limited.

To sum up, by providing an objective approach to revise weights based on known ratios between criteria, the methodology addresses a crucial need for more accurate assessments in evaluating potential solar PV farm locations. Beyond its application in solar PV farm site selection, the methodology offers versatile contributions. Firstly, it can enhance decision-making in various renewable energy projects by aligning AHP calculations with known ratios, ensuring more reliable results for optimal project locations. The methodology's focus on minimizing changes in weights, except for known ratios, contributes to the overall consistency of MCDM models, promoting reliability in decision analyses across diverse fields. Moreover, when integrated with GIS technologies, the methodology can further improve spatial analysis and decision support capabilities in the context of solar energy infrastructure planning. This integration holds potential applications in broader sustainable energy development initiatives. Furthermore, the iterative optimization cycles of the methodology provide a systematic approach to incorporate expert opinions into the decision-making process. This feature is particularly valuable in scenarios where expert knowledge is crucial but requires refinement for more accurate outcomes.

5. Conclusions

In the present study, a novel approach is proposed for the site selection of solar PV panels. This approach is a procedure for the revision of the initial matrix of the AHP method. The revision is needed to satisfy a predefined relation in the final weights of the AHP method. Accordingly, an objective relation manifested by experts is not affected by other relations. This protective measure is justified by the calculable relation established between these constraints, primarily grounded in the construction-phase expenditure associated with the relevant criteria. A relation is established between the two criteria used in the selection of solar PV farms, namely, the transmission line and road expenditures for the Kayseri Province. Accordingly, the initial matrix of the AHP method is revised by the proposed approach. Revised weights are different from the ones of the conventional AHP method. The difference in weights of constraints changes from 13.5% to 7.2%. As a result, the changes in the area of suitability regions range from 3.4% to 50%. The revision of AHP weights leads to a reduction in higher-suitability areas, accompanied by a notable expansion in the region exhibiting lower (20-40%) suitability.

The methodology enhances the accuracy of assessing potential solar PV farm locations by objectively adjusting weights based on known ratios between criteria. This approach addresses a critical need for more precise evaluations, resulting in increased accuracy and reliability in site selection studies. Additionally, the methodology also has broader implications for decision-making in renewable energy projects, multi-criteria decision analysis, GIS integration, and the incorporation of expert opinions. Its systematic approach enhances the reliability and objectivity of decision support systems, especially in renewable energy planning.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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