

Integration of Multi-Criteria Analysis (AHP) and Geographic Information Systems to Optimize the Selection of Photovoltaic Sites: Application to the Thies Region, Senegal

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Abstract

Faced with the energy transition challenges in sub-Saharan Africa, this study proposes a methodological framework combining Geographic Information Systems (GIS) and the Analytic Hierarchy Process (AHP) to optimize photovoltaic site selection in the Thies region of Senegal. Seven decision criteria were considered: solar irradiation, mean annual temperature, slope, terrain aspect, and proximity to power lines, main roads, and urban areas, weighted using real data from atmospheric sensors and geospatial platforms. Restricted areas (protected zones, urban areas) were excluded via buffer constraints. Results show that 14.12% of the regional territory (672 km²) is suitable for large-scale PV installations, primarily concentrated in the central and northeastern parts of the region, around the city of Thies, and in the southwestern department of Mbour. A sensitivity analysis conducted under three weighting scenarios (AHP, equal weights, high economic weights) confirms the robustness of the results and highlights the critical role of economic factors in site selection. The findings are validated against existing solar plants at Malicounda and Touba Toul. This research provides a valuable decision-support tool for energy planners, aligned with Senegal's sustainable development objectives for 2030.

Keywords

Photovoltaic Solar Energy, Analytic Hierarchy Process, Multi-Criteria

1. Introduction

Technologies that use Renewable Energy Sources (RESs) offer great potential because they are natural, free, renewable, and accessible worldwide. These include solar, wind, biomass, and geothermal energy. Many countries have adopted strategies to integrate these energy sources into their sectors, promoting a sustainable, secure, and low-carbon future.

Large-scale photovoltaic installations, deployed in areas with high solar irradiance, offer significant potential. However, the inconsistency and variability of this irradiance pose major challenges. Site selection requires a thorough analysis that takes into account the quality of the land, proximity to infrastructure to reduce costs, and the optimization of energy production. A strategic site analysis is essential to ensure high-performing and profitable projects.

Optimizing site selection for solar photovoltaic power plants is a major challenge in the energy transition, particularly in countries such as Senegal, where solar resources are abundant but underutilized due to the geographic, social, and economic complexities of the regions, as explained in the preceding paragraphs. In this context, the Thies region, located in an area with high solar potential, serves as a relevant case study for developing a more effective approach to site selection for photovoltaic installations. However, site selection is not limited to identifying areas with high solar radiation; it must also take into account multiple criteria such as proximity to transportation infrastructure, access to power grids, ecological characteristics, and the social and economic impacts of the projects. Thus, the central issue of this study is the following question: How can site selection for the construction of solar photovoltaic power plants in the Thies region be optimized using a multi-criteria approach integrated with Geographic Information Systems (GIS)? This issue raises several technical and methodological challenges, including the selection and weighting of criteria, the management of complex geospatial data, and the integration of multi-criteria analysis into a decision-making framework that takes local specificities into account. It is also crucial to determine to what extent this approach can contribute to a more balanced geographic distribution of solar power plants, reduce installation costs, maximize energy yields, and minimize negative impacts on local communities and the environment.

The study aims to develop an effective and adaptable optimization model capable of incorporating these various criteria and identifying strategic sites for the future development of solar photovoltaic power plants in the Thies region, while contributing to Senegal's energy policy and its sustainable development goals.

To address these challenges, multi-criteria methods simplify decision-making by incorporating various factors. Large-scale photovoltaic projects (at least 5 MW) benefit particularly from these approaches, as demonstrated by several studies that

highlight their effectiveness in energy planning [1] [2].

Geographic Information Systems (GIS) also play a crucial role in the selection of energy sites [3] [4]. A three-step decision-making process is recommended [5]: identify criteria and constraints, rank sites using a weighted model, and analyze the sensitivity of the criteria.

This study, conducted in the Thiès region, aimed to identify the optimal sites for the installation of photovoltaic power plants. Seven criteria were considered to demonstrate that photovoltaic (PV) technology is the most promising. A model combining the Analytic Hierarchy Process (AHP) and GIS was developed to integrate geographic data and subjective criteria, thereby providing effective decision-support tools.

The main objective was to propose an innovative approach based on real-world data from atmospheric sensors in order to generate criteria layers. Information on solar radiation and air temperature, calculated in ArcGIS, was incorporated into the AHP process to identify the most suitable sites in the Thiès region.

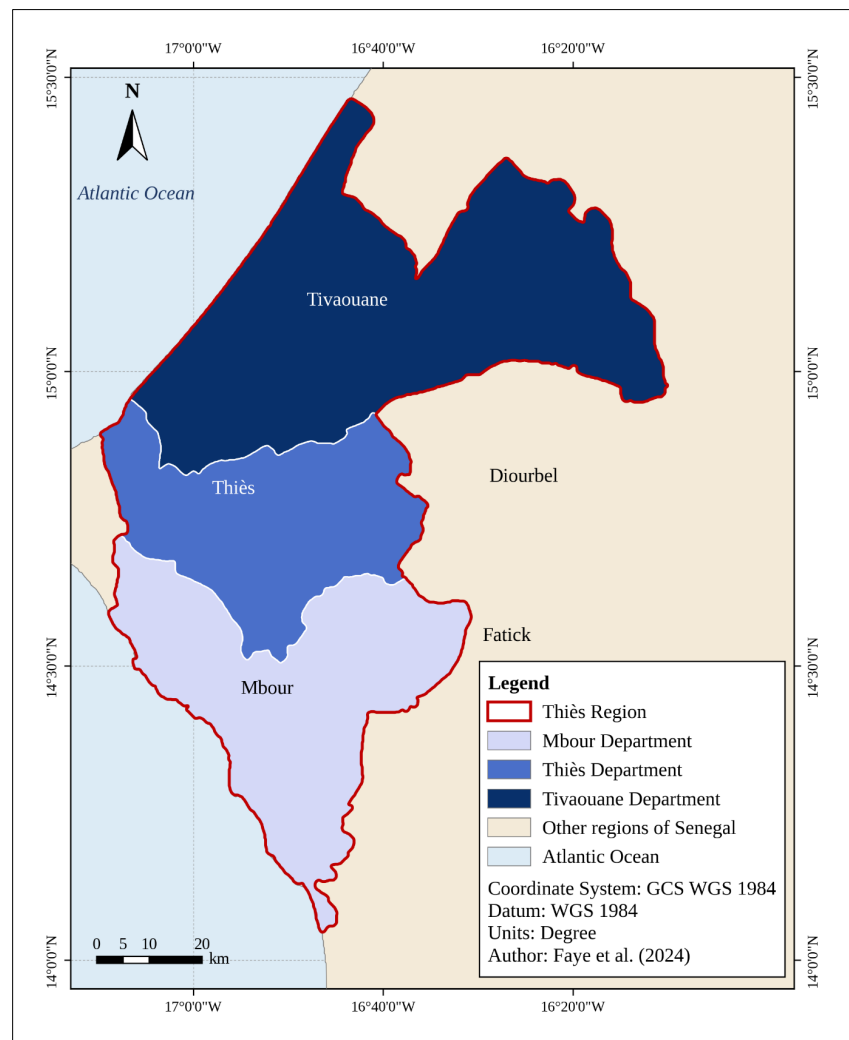


Figure 1. Location of the Thiès region.

2. Study Area

The Thies region is located in western Senegal (**Figure 1**), about 70 km from Dakar, and forms a ring around the Cape Verde Peninsula. It covers an area of 6601 km², or 3.4% of the country's total land area. The region's terrain is mostly flat, with the exception of the Thies hill, which rises to 105 m. It also includes the Diass Massif, which rises to 90 m, as well as the Thies Basin, which covers 65 km² and reaches a maximum elevation of 128 m [6]. The region's climate is mild and favorable, with an average temperature of around 32°C in summer. The region is located in a transitional zone influenced by maritime trade winds and the harmattan.

Data from population projections based on the 2023 Census estimate the resident population of the Thies region at 2,467,523, compared to 1,838,366 in 2013. Between 2002 and 2023, the region's population grew from 1,331,916 to 2,467,523 [7].

3. Methods

3.1. Data Used

The thematic layers for protected areas in this study were obtained from government agencies, while the buffer distances were taken from the literature, as shown in **Table 1**. The total area of existing and proposed protected lands represents approximately 10.42% of the country's total land area.

Table 1. Restrictions being considered for large-scale PV projects in Thies.

Restrictions	Sources	Buffer Zone	References
Protected Areas	www.senegal.africageoportal.com	<1000 m	[8]
Major Roads	www.geosenegal.gouv.sn	<500 m	[9]
Towns and Cities	www.openstreetmap.org	<1000 m	[10]

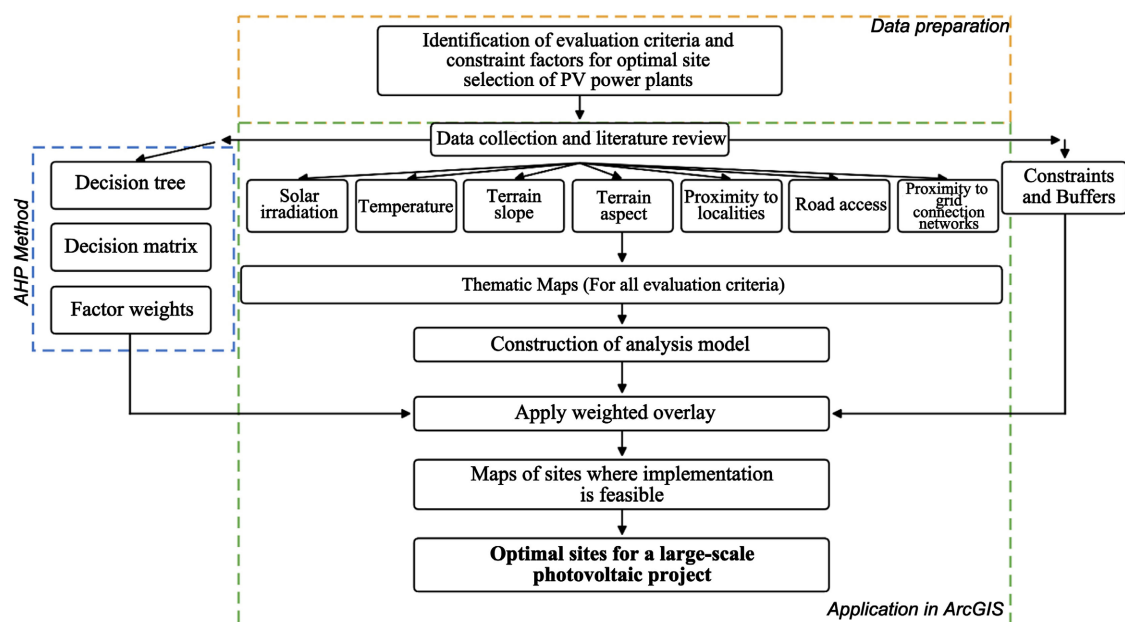


Figure 2. Methodological flowchart for selecting sites for the installation of PV power plants.

In this study, a multi-criteria analysis was used to evaluate the suitability of sites for the construction of solar photovoltaic power plants. **Figure 2** shows the main steps of the methodology used.

3.2. Land Suitability Index (LSI)

For greater clarity and in-depth analysis, the Land Suitability Index (LSI) was highlighted. This indicator measures the suitability of each site for the installation of solar photovoltaic (PV) power plants, taking into account established criteria while excluding prohibited or unsuitable areas. Details of the Land Suitability Index values are presented in **Table 2**.

Table 2. Site adaptability index.

Scale Value	Land Suitability Index
10 - 40	1 (Less suitable)
40 - 50	2 (Slightly adapted)
50 - 60	3 (Moderate adaptation)
60 - 70	4 (Highly suitable)
70 - 100	5 (The most appropriate)

3.3. AHP for Weighting Criteria

To identify the best sites for installing solar photovoltaic power plants, the problem was structured as a hierarchical model, as shown in **Figure 3**. The criterion used to select the most suitable site for installing large-scale photovoltaic power plants was at the top level of the hierarchy. The decision criteria are represented at the second level of the model.

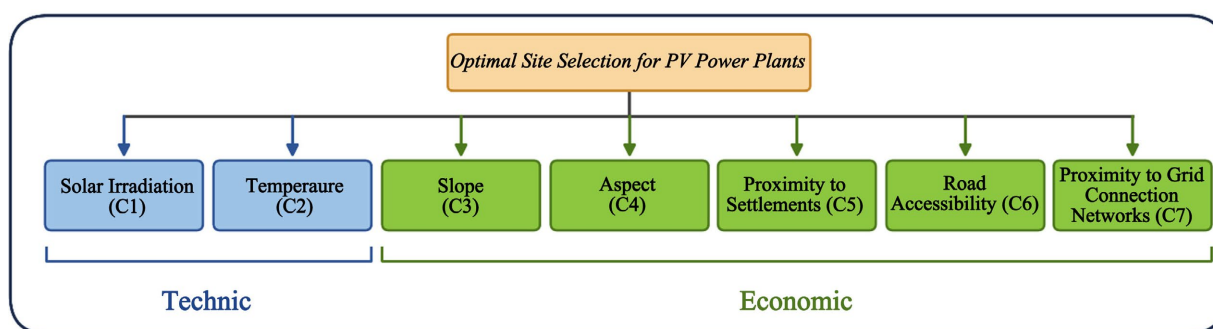


Figure 3. Decision criteria considered for the selection of solar PV sites.

The next step was to develop a matrix for comparing criteria, including solar radiation, average annual temperature, slope, land aspect, proximity to an urban area, proximity to a major road, and proximity to power lines. All of these factors were intended to help achieve the study's objective within the proposed decision-making framework. Arán Carrión *et al.* [11] introduced an approach for deriving a pair-wise comparison matrix and determining the priority weights of the crite-

ria. Several points supported the rationale behind the weighting of the criteria.

First, climatic parameters, such as solar radiation and average annual temperature, are considered the most important criteria, as they determine the energy output of the photovoltaic power plant. Next are the criteria of slope and aspect, which determine the amount of sunlight received by the solar panels. Their importance depends primarily on the slope of the land and the orientation of the site. Moderate slopes and south-facing sites are considered to be highly significant factors.

In addition to the two criteria mentioned above, the distance to the power grid, major roads, and cities is a key factor given its significance, as it determines infrastructure and transmission costs during installation. Based on this logic, and taking into account the weightings of the criteria presented in similar studies on the suitability of sites for solar power plants [12]–[16], the pair-wise comparison matrix was established, as shown in **Table 3**. The importance of these criteria is also emphasized by strategic organizations such as the NREL and the Environmental Protection Agency (EPA) in the United States [16] [17].

Table 3. Decision criteria comparison matrix.

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	1	2	3	4	7	6	5
C2	1/2	1	2	3	6	5	4
C3	1/3	1/2	1	2	5	4	3
C4	1/4	1/3	1/2	1	4	3	2
C5	1/7	1/6	1/5	1/4	1	1/2	1/3
C6	1/6	1/5	1/4	1/3	2	1	1/2
C7	1/5	1/4	1/3	1/2	3	2	1

Finally, it was necessary to calculate the priority weights and check for inconsistencies. The eigenvector, which provides the priority weight for each criterion, was calculated, and the sum of all weights equals one, as shown in **Figure 4**. To verify the weighted values of each criterion, the CR was calculated ($CR = 0.02$); since it is less than 0.10, the value judgments are considered acceptable [18].

At this stage, seven layers representing the criteria under consideration, along with their corresponding weights (derived from the AHP tool), had been generated. Using the weighted sum overlay tool in the GIS, the selection of sites for photovoltaic power plants was approached as follows [19].

Since the input layers have different values and ranges, each criterion must be scaled to a common scale in order to integrate them into a single layer. Subsequently, the values in the input maps were reclassified according to a common preference scale ranging from 10 to 100 (with 100 being the most suitable).

Each criterion layer is multiplied by the criterion's weight or importance according to the AHP.

The resulting values from the cells were summed to generate the final combined layer. Consequently, the alternatives are the potential sites generated by the GIS, which takes into account the criterion weights obtained using the AHP technique.

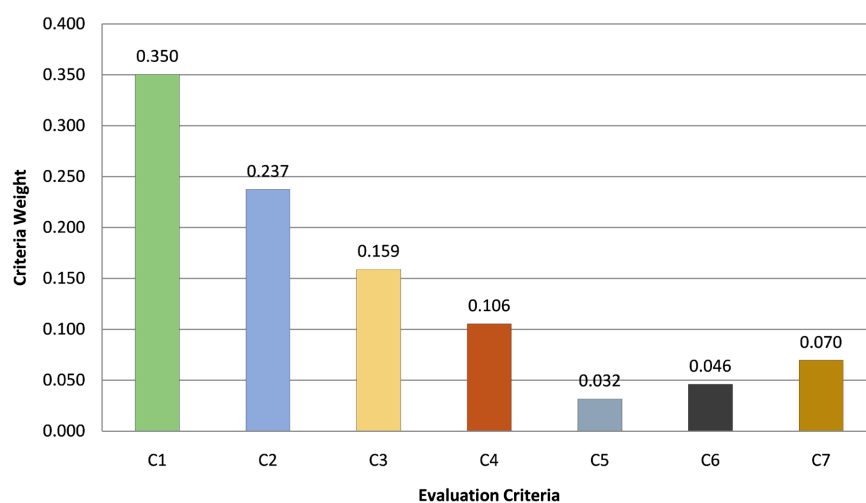


Figure 4. Weighting factors for the criteria.

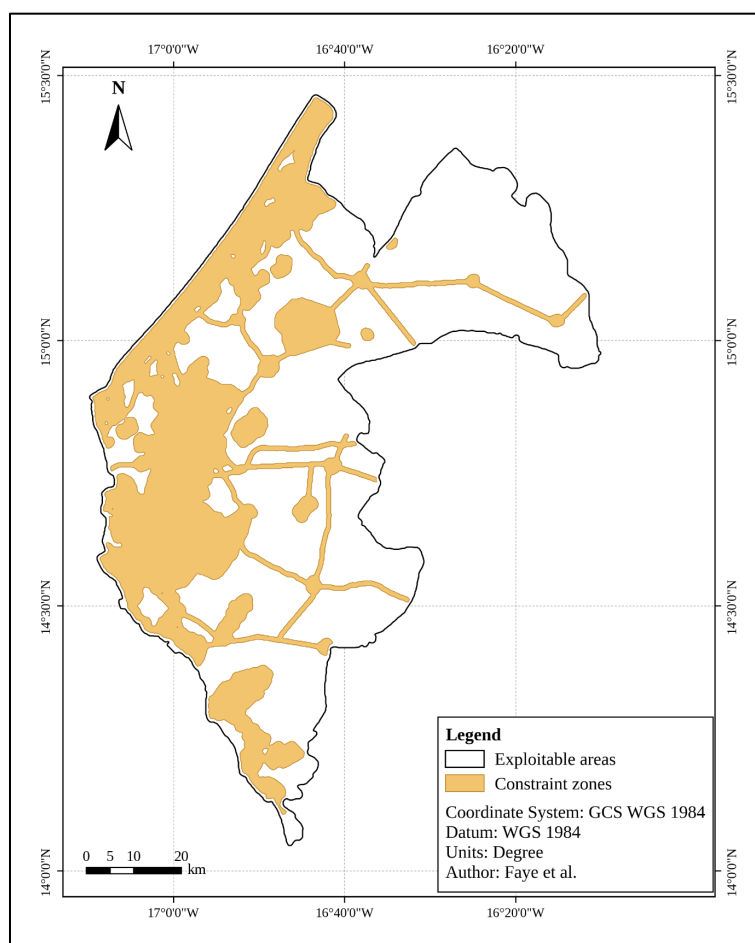


Figure 5. Map of restrictions in the region.

4. Results

4.1. Selection of Potential Sites

The methodology applied to the Thies region made it possible to identify sites suitable for the installation of large-capacity photovoltaic power plants. The final results, illustrated by a map of unsuitable areas, reveal that a significant portion of the territory is subject to restrictions, particularly protected areas and urbanized areas, as shown in **Figure 5**. In contrast, the remaining areas, considered favorable, offer strong potential for the installation of large-scale solar photovoltaic power plants.

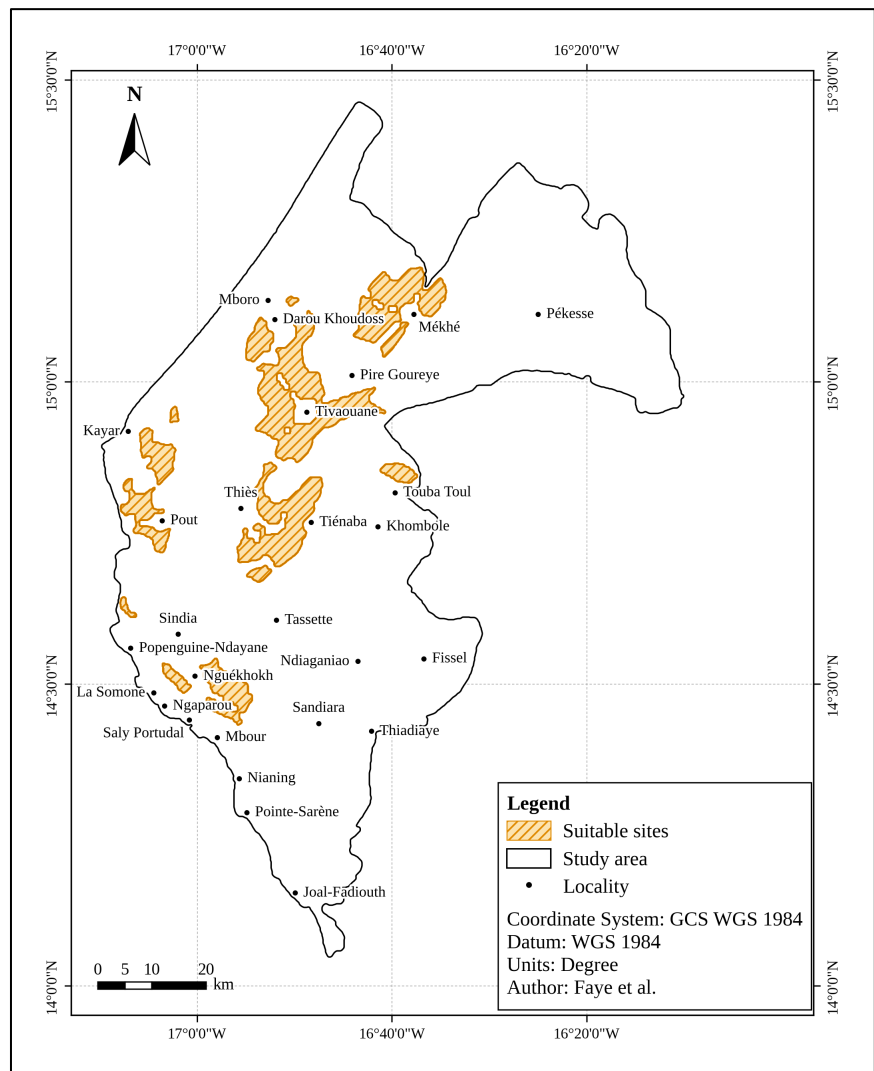


Figure 6. Preliminary results for potential sites.

The analysis combining the MCDM method and GIS produced a map showing that 14.12% of the study area or 672 km² is particularly suitable for the installation of large-scale photovoltaic power plants, as illustrated in **Figure 6**. The central region of Thies stands out for its large number of favorable areas, attributable to high

levels of sunshine, moderate slopes, and strategic proximity to major roads, power lines, and urban areas.

In addition, a few sites located to the north and northwest of the study area were also suitable. In contrast, the northern coast is characterized by a wide strip of unsuitable areas. Conversely, the southeastern part, particularly in the department of Mbour, was especially suitable for such facilities, thanks to favorable climatic conditions and a high density of major roads, power transmission lines, and urbanized areas.

4.2. Site Selection for Photovoltaic Power Plants

The study showed that most scores range from 30 to 80, with an average of 60 on a standardized scale ranging from 10 to 100 [17]. The LSI analysis shows that many highly suitable sites are concentrated in the central and northwestern parts of the Thies region, as shown in **Figure 7**. The moderately suitable areas were mainly located in the southeast, due to higher solar radiation and lower air temperatures. In contrast, the northern and western coastal areas had lower feasibility scores, primarily due to low air temperatures. The eastern part of the study area showed moderate to high feasibility, benefiting from high solar radiation.

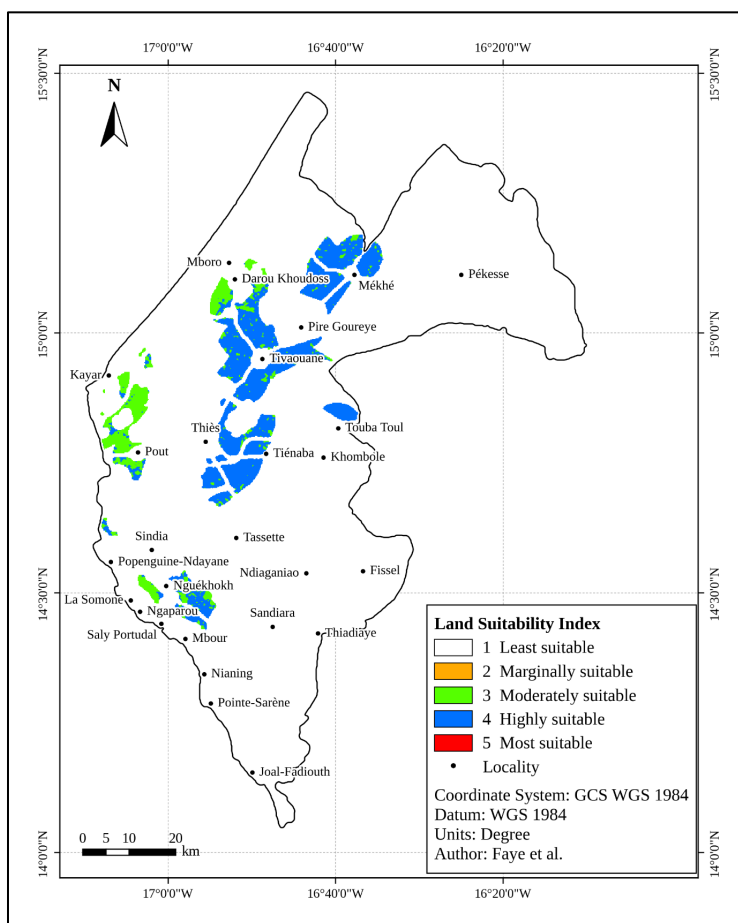


Figure 7. Results of the suitability index using AHP weights.

According to the model's results, the areas around Tivaouane and Meckhe, located in the north, as well as the central area of Thies, stood out as being among the most suitable sites for the construction of large-scale photovoltaic power plants. Although these regions account for only 6% of the areas identified as favorable, they offer strong potential for high-performing projects, combining optimal solar production with manageable infrastructure costs. In contrast, the areas around Kayar and Pout, as well as those near the north and northwest coasts, are considered moderately suitable due to lower air temperatures and limited resources.

The map of suitable areas produced in this study is a key tool to help decision-makers select the optimal sites for large-scale solar power plants. Recently, Senegal has launched several solar and wind projects totaling 266 MW in various parts of the region [20]. For example, in the Tivaouane department, two photovoltaic projects, each with a capacity of 60 MW in Mérina Dakhar and Méouane, benefit from a strategic location near highly suitable sites, which enhances their appeal for solar technology and ensures maximum performance. This map showing suitable areas provides decision-makers with valuable information to effectively anticipate and plan solar projects, while contributing to Senegal's energy diversification goals as part of its Vision 2030.

4.3. Weighting and Consistency of the AHP Matrix

Various scenarios for weighting the criteria were considered, and their overall impact on the site feasibility index (LSI) was evaluated. In addition to the weights assigned using the AHP method, two scenarios were examined in this study: equal weighting and greater weighting of the economic criteria.

In the equally weighted scenario, a weight of 14.28% was assigned to each criterion, without taking their relative importance into account. This approach is a simple decision-making method designed to reduce risks. Conversely, in the scenario where economic criteria such as slope, land orientation, and proximity to urban areas, power lines, and major roads are given greater weight (16% each), the objective was to assess the influence of economic factors. **Figure 8** illustrates the weightings of the criteria for the AHP method, the equal-weighting method, and the high-economic-weighting scenario.

Alternative sites were evaluated and ranked for the development of large-scale solar photovoltaic projects using equal weighting for all criteria. This scenario allows for a uniform measurement of the criteria's influence on the resulting feasibility layer and provides a better understanding of the relative importance of each criterion. Compared to the AHP methodology, the total area of favorable zones increased by 0.09% (672.24 km²) of the study area. This increase is primarily due to the higher weightings (14.28%) assigned to the factors.

Similar to the AHP approach, the results of the equal-weighting scenario show that a large portion of the suitable areas have a high LSI, accounting for approximately 48% of the favorable area. However, the marginal and highly suitable feasibility indices decreased slightly but significantly, from 1.11% to 1.04% and from 7.62% to 5.81%, respectively, across the entire study area (**Figure 9**).

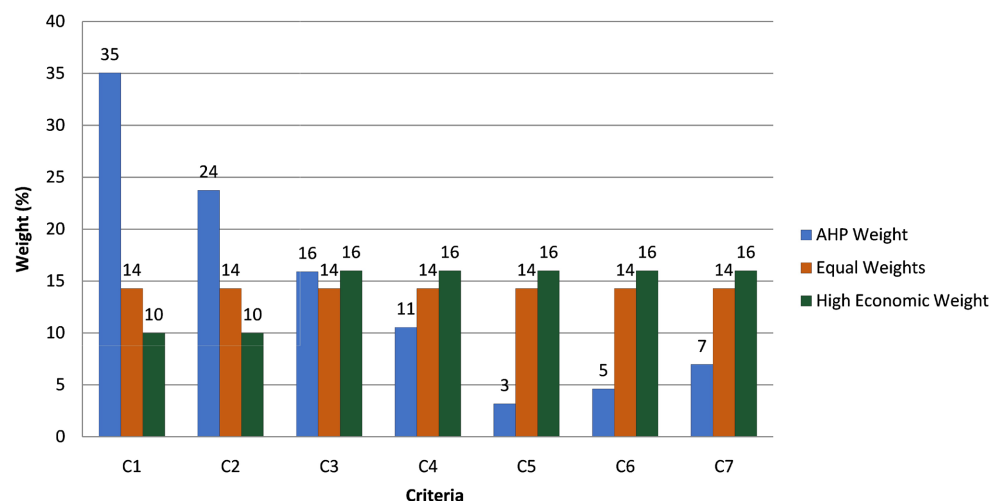


Figure 8. Weighting of decision criteria based on different scenarios.

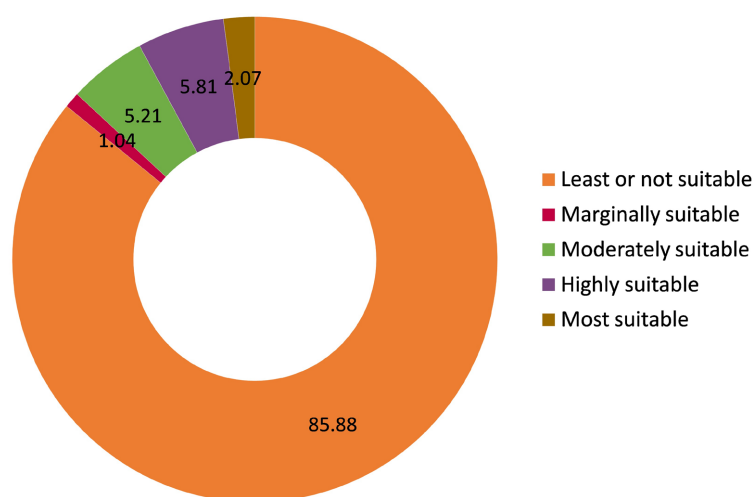


Figure 9. Distribution of the aptitude index for an equal-weighting scenario.

The highest adaptability index (LSI) increased slightly, from 14.28% to 14.64% of favorable areas (or from 2.02% to 2.06% of the study area) when equal weights were applied to all criteria. The majority of areas with moderate to high LSI are located near the central city, as shown in **Figure 10(a)**. In the southwestern regions along the west coast, more moderately suitable and highly suitable sites were identified, as the weighting for slope decreased by 2% (from 15.9% to 14.3%). In the Northeast, moderately suitable areas improved to become very suitable or most suitable, due to higher weightings for economic factors and lower weightings for temperature-related criteria.

Since solar photovoltaic systems require high initial investments and large tracts of land, construction costs become a crucial factor. Thus, proximity to national power grids, major roads, and urban areas can entail significant economic costs, which may sometimes offset the benefits of the electricity generated by a solar power plant. Consequently, selecting sites based on slope, orientation, and prox-

imity to existing infrastructure is essential for the development of solar projects. Assigning higher weights to economic criteria including slope, land orientation, and proximity to urban areas, roads, and power lines may be a viable solution. In this scenario, the results show that the most suitable areas are approximately three times larger in terms of land area compared to the equal-weighting and AHP scenarios (**Figure 10(b)**). The central zone, where the necessary infrastructure is in place, has a high concentration of areas with very high LSI scores. Although the lowest LSI score has increased slightly, the moderate and marginal feasibility indices have decreased compared to the equally weighted scenario. The results of the various scenarios demonstrate the sensitivity of the analysis to the weightings of the criteria, thereby yielding different distributions of site feasibility. **Table 4** presents the final results obtained by varying the weightings, confirming that economic and technical factors play a key role in the evaluation of the study area.

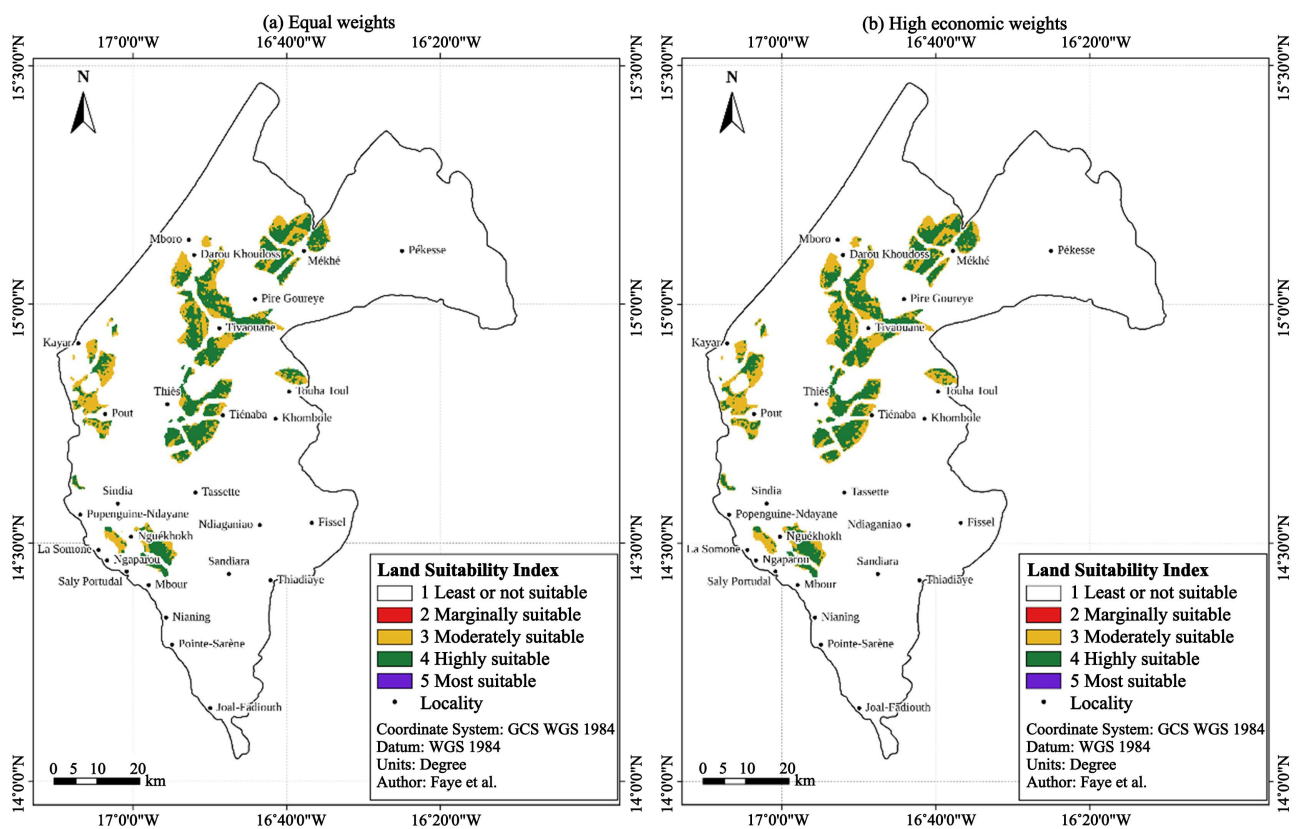


Figure 10. Land suitability results based on equally weighted criteria (a) and highly weighted economic factors (b).

Table 4. Distribution of land suitability based on different scenarios for the study area.

Weighting Scenario	Weight	Distribution of Site Adaptability (%)				
		5	4	3	2	1
AHP	Tech = 0.58	2.02	7.63	3.37	1.11	85.88
	Eco = 0.42					

Continued

Equal Weights	Tech = 0.5 Eco = 0.5	2.07	5.81	5.21	1.04	85.88
High Economic Weight	Tech = 0.2 Eco = 0.8	2.14	5.80	5.15	1.03	85.88

5. Discussion

Despite the robustness of the sensitivity analysis, several sources of uncertainty affect the reliability of the results. The AHP's pairwise comparisons, although validated by an acceptable consistency ratio ($CR = 0.02$), are still based on expert judgment and therefore remain subject to a degree of subjectivity that a purely quantitative method cannot completely eliminate. The reclassification of continuous criteria such as solar irradiance, temperature, and slope on a common scale ranging from 10 to 100 also introduces threshold effects that can cause a site to shift from one suitability class to another, a limitation already noted in comparable AHP-GIS applications elsewhere [16]. As noted earlier, the limited number of stations used for spline interpolation of temperature restricts the spatial accuracy of this layer, and the buffer distances applied to protected areas, roads, and urban areas were derived from the general literature rather than calibrated to Senegalese land-use regulations, a simplification that similarly affects suitability studies based on natural conditions conducted in other regions [21].

Another limitation concerns the socioeconomic dimension of the analysis. The model is based on seven technical and infrastructural criteria but does not directly incorporate land tenure status, land acquisition costs, or customary usage rights common in rural Senegal, all of which strongly influence the feasibility of projects in practice. Demographic data were used only to characterize the study area and not as a weighted decision criterion; social acceptability, local employment benefits, and community engagement factors increasingly recognized as key determinants of the successful implementation of large-scale solar projects in comparable West African contexts were not assessed [22].

These limitations suggest several avenues for improving the model. Replacing or supplementing the classical AHP with a fuzzy or intuitionistic-fuzzy AHP would better capture the inherent uncertainty in expert judgment and the reclassification of criteria, while a Monte Carlo simulation could be used to propagate uncertainty throughout the suitability index rather than relying on a fixed set of three weighting scenarios, as has been demonstrated in recent hybrid GIS-MCDM applications in sub-Saharan Africa [23] [24]. In terms of data, increasing the density of the temperature and irradiance monitoring network, as well as defining buffer zones based on Senegalese land-use regulations, would strengthen the technical layers. Finally, the explicit integration of socioeconomic layers such as land prices, tenure status, population growth projections, and measures of social acceptability into the multi-criteria framework, following approaches already tested in comparable West African contexts, would make the suitability index more directly usable by planners

and investors [22].

6. Conclusion

This study explores the potential of sites suitable for large-scale photovoltaic projects in the study area, using GIS and the MCDM tool. The AHP method is used to evaluate the relevance of each decision criterion in selecting the best sites for photovoltaic power plants. The criteria considered in this model include solar radiation, average annual temperature, slope, land orientation, and proximity to infrastructure such as power lines, major roads, and urban areas. Applying this methodology generates a land suitability index for areas that are ideal for the construction of grid-connected photovoltaic power plants. The most suitable areas are located primarily in the central and northeastern parts of the region, as well as in the southwest in the department of Mbour, near the western coast. These areas account for 50% of the most suitable locations, concentrated mainly around the central city (Thies), which has the highest population density. The northeastern part of the region has a moderate-to-high suitability index due to its well-developed infrastructure and high levels of solar radiation.

Author Contributions

C.S.F. and E.B. conceptualised the study, developed the software, designed the methodology and curated the data. C.S.F. validated the results and wrote the first draft of the manuscript. C.S.F., H.S. and M.F. also reviewed and edited the manuscript. E.B. provided the dataset and the industrial context and reviewed the manuscript. All authors read, approved and agreed to the published version of the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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