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RESEARCH ARTICLE

A GIS–AHP Framework for Solar Energy Site Selection in Developing Regions: Urcuqui, Ecuador

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Abstract

Global warming and climate change challenge us to implement sustainable energy systems. Urcuqui, located in the Imbabura province in the North of Ecuador, is one of the cities with the most promising renewable energy resources. Therefore, analyzing the energy potential of Urcuqui at the micro and macro scales will provide valuable information for the national efforts to pursue the Sustainable Development Goals and the 2030 Agenda. This work aims to identify strategic points with high viability to implement renewable energy systems by collecting information from local governments, such as Municipio de Urcuqui and Prefectura de Imbabura, and implementing advanced methodologies like GIS and multi-criteria analysis. This research focuses mainly on solar and hydrological resources, which have been identified as the most significant energy sources and have the potential to be applied in different areas where required. As the intention is to give people and small communities access to affordable and clean energy, this investigation also incorporates demographic factors and environmental sustainability. The result illustrates Urcuqui parish as the main feasible area to implement PV systems, with approximately 43% of the canton's suitable area. The results show the importance of assessing the geological and technical aspects of the geological resources. They are expected to provide valuable information for regional decision-makers regarding energy policies and promoting more sustainable and environmentally friendly development.

Keywords: renewable energy, PV, hydropower, sustainable development.

1 Introduction

The world is facing a significant energy problem. As the world's population grows and electricity consumption increases, energy demand continues to rise [1]. By 2040, energy demand is expected to increase 56%, and by 2050, reserves may become critically low [2]. With fossil fuels as the main source of energy and the global population expected to reach 9.7 billion people by 2050 , traditional fossil fuel energy systems will be unsustainable and unable to provide and support energy demand [3, 4]. Many European and American countries still depend heavily

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on fossil fuels despite limited resources [5]. In the USA only, fossil fuels have historically dominated energy production, accounting for 79% of total primary energy until 2012 [6]. Similarly, Central Asian countries follow the same trend, keeping their dependence on fossil fuels,while the adoption of renewable energy resources is still minor in comparison with fossil fuel due to logistical and economic challenges [7] . These statistics show the global energy trends and highlight the urgent need for a transition to renewable energy to mitigate environmental degradation and ensure environmental sustainability.

Dependence on fossil fuels for energy generation creates a large disparity in energy access between urban and rural communities. Studies by [8] indicate that more than 50% of the world's population lives in rural regions, with the majority (3 billion people) concentrated in developing countries. However, about 1.6 billion rural residents in these countries still lack reliable access to energy sources, highlighting an unequal electricity distribution between rural and urban areas [9]. Energy studies from countries such as India and Africa highlight that dependency on fossil fuels to generate energy increases disparities in access to electricity, leaving rural areas far behind their urban counterparts [10, 11]. Inaccessibility to electricity limits the growth of rural communities, affecting their social and economic context, underscoring the critical need to implement energy systems that provide decentralized renewable solutions [12, 13].

Between 2010 and 2020, photovoltaic and wind power installations reached record levels [14]. The development of renewable energy sources such as solar, wind and hydropower has gained global momentum as countries work to reduce carbon emissions and mitigate climate change [15]. Solar (36.67%), hydro (32.76%) and wind (26.29%), represent significant percentages of global renewable capacity [16]. Moreover, some nations such as Iceland (100%), Norway (97%) and Costa Rica (93%) already achieve high percentages of renewable energy production, especially through hydropower [17]. China is the country that leads the growth in renewable energy, with hydroelectric and photovoltaic systems of low and large scale, providing equal access to electric power and promoting the development of rural communities [18].

Although solar energy is very promising, most feasibility studies in Latin America are focused in large scale systems, ignoring the potential of small-scale systems adapted to local conditions [50]. Due to its location in the intertropical zone, Ecuador becomes a zone of high interest, with great geographical characteristics, natural resources, and climatic conditions to implement small-scale solar systems [19]. Urcuqui, located in northern Ecuador, presents an exceptional potential of solar irradiation [20]. Even so, 28% of rural homes have no reliable electricity. [22], identifying optimal locations for implementing renewable energy systems in Urcuquí will significantly improve sustainable energy access, while supporting climate change mitigation [21]. This study conducts a comprehensive evaluation of Urcuqui's micro-scale energy potential, using multi-criteria analysis based on evidence to provide practical recommendations to policymakers and residents, accelerating the region's transition to sustainable energy independence.

2 Related Work

The implementation of small-scale renewable energies has become increasingly important in recent years, particularly in the context of climate change and the global energy transition. The implementation of small-scale energy systems aims to mitigate the impact of climate change on society and decentralize energy production to achieve the 2030 Agenda for sustainable development [23]. While the global potential for solar energy is vast, implementing effective planning tools at the local level remains a critical challenge in Ecuador, which is still focused on large-scale energy production, with few preliminary studies conducted at the local level.

2.1 Ecuador's Energy Landscape and Solar potential

Table 1. Main photovoltaic projects in operation or under development in Ecuador. Adapted from [27].

Project	Capacity (MW)
El Aromo (Manabí)	200
Ñañapura	60
Intiyana Solar	60
Tren Salinas	60
Imbabura Solar	60
Urcuqui (Imbabura)	60

Ecuador's electricity demand has grown steadily (approximately 200 MW/year), reaching 28,181 GWh in 2022. The residential (35%), industrial (28%), and commercial (18%) sectors are the largest consumers [24]. Despite a nominal generation potential of 9,252.92 MW, only 3,687 MW of power was effectively

Table 2. Applied Techniques and Criteria for PV Systems by Location

Technique	Location	Criteria	Ref.
AHP, MCDA	Al-Qassim/SA	Irradiance, Protected areas, NDVI, slope, powerlines, roads	[28]
AHP	Philippines	DNI, protected areas, slopes, water distance, land cover, road distance, grid capacity, typhoon frequency	[29]
AHP, GIS-MCDM	Ningxia/China	Irradiation, temperature, protected areas, land cover, transport, slope, grid proximity	[30]
GIS-MCDM, AHP, WRF	Malawi	Irradiation temp., slope, aspect, elevation, road distance, grid distance, settlement distance	[31]
GIS (NREL)	Fujian/China	DEM, Irradiation, Land cover, Reserves, Atmospheric data, Socioeconomic	[32]
GIS, AHP, LSI	Cantabria/Spain	Irradiance, temperatures, orientation, humidity, latitude, slope, protected areas, land use, road proximity, power proximity	[33]

delivered in 2024, revealing a significant gap of 4,567 MW. To bridge this gap, Ecuador needs to add 250–300 MW of new generation capacity each year, a target that has not been met in recent years [9]. As of 2023, only 93 MW of PV capacity was installed [25], and while long-term estimates project a contribution of 5.7 GW by 2050 [26], current projects remain predominantly large-scale, as illustrated in Table 1.

2.2 GIS-MCDA Methodologies for Solar Site Selection

To effectively harness solar potential, robust spatial planning methodologies are crucial for identifying optimal locations while minimizing environmental and social impacts. Geographic Information Systems-based Multi-Criteria Decision Analysis (GIS-MCDA) has emerged as a key model for this task, integrating geographical data with weighted criteria for a comprehensive and accurate understanding of geographical factors to ensure the correct operation of solar energy systems.

Table 2 summarizes relevant studies with a consistent methodological framework. Conventional studies, such as those by [28] in Saudi Arabia and [29] in the Philippines, demonstrate the standard application of the Analytic Hierarchy Process (AHP) within a GIS [49]. These studies generally use a standard set of criteria – including solar irradiation, slope, proximity to electrical grids and roads, and land-use restrictions – to generate comprehensive suitability maps. Also, more advanced methodologies have incorporated scenario-based analysis and advanced data modeling. As an example, [30] applied AHP under distinct economic, technical, and environmental scenarios, producing multiple suitability findings that provide planners with flexible decision-making pathways. Similarly, [31] refined the accuracy of the solar resource assessment by integrating data from the Weather Research and Forecasting (WRF) model, moving beyond static irradiation maps to a more dynamic and precise evaluation. As demonstrated in the literature, AHP within a GIS-MCDA framework is a flexible and powerful tool. Furthermore, advanced studies are incorporating dynamic climate data and multi-scenario analysis to improve the practical applicability of their findings.

2.3 Research Gap and Contribution

Although solar energy shows great promise, most feasibility studies in Latin America focus on large-scale systems, overlooking the unique potential and constraints of small-scale systems. Current national plans and projects predominantly concentrate on large-scale areas (Table 1), resulting in a significant gap regarding local suitability analysis. This gap can provide an opportunity to empower municipalities, communities, and small businesses.In Ecuador, there is a lack of studies focusing on small-scale, decentralized solar deployment, despite the country's geographical diversity. In the Ecuadorian Andean region, a number of distinct challenges are found, including high-altitude topography, complex microclimates, seismic activity, land use conflicts, and socio-economic dependencies on agriculture.

This study aims to address this gap by developing a customized GIS-based AHP and Binary Logic model for the city of Urcuqui in Imbabura, Ecuador. It adapts global methodological best practices and applies a detailed set of climatic, socioeconomic, and environmental criteria relevant to the Andean

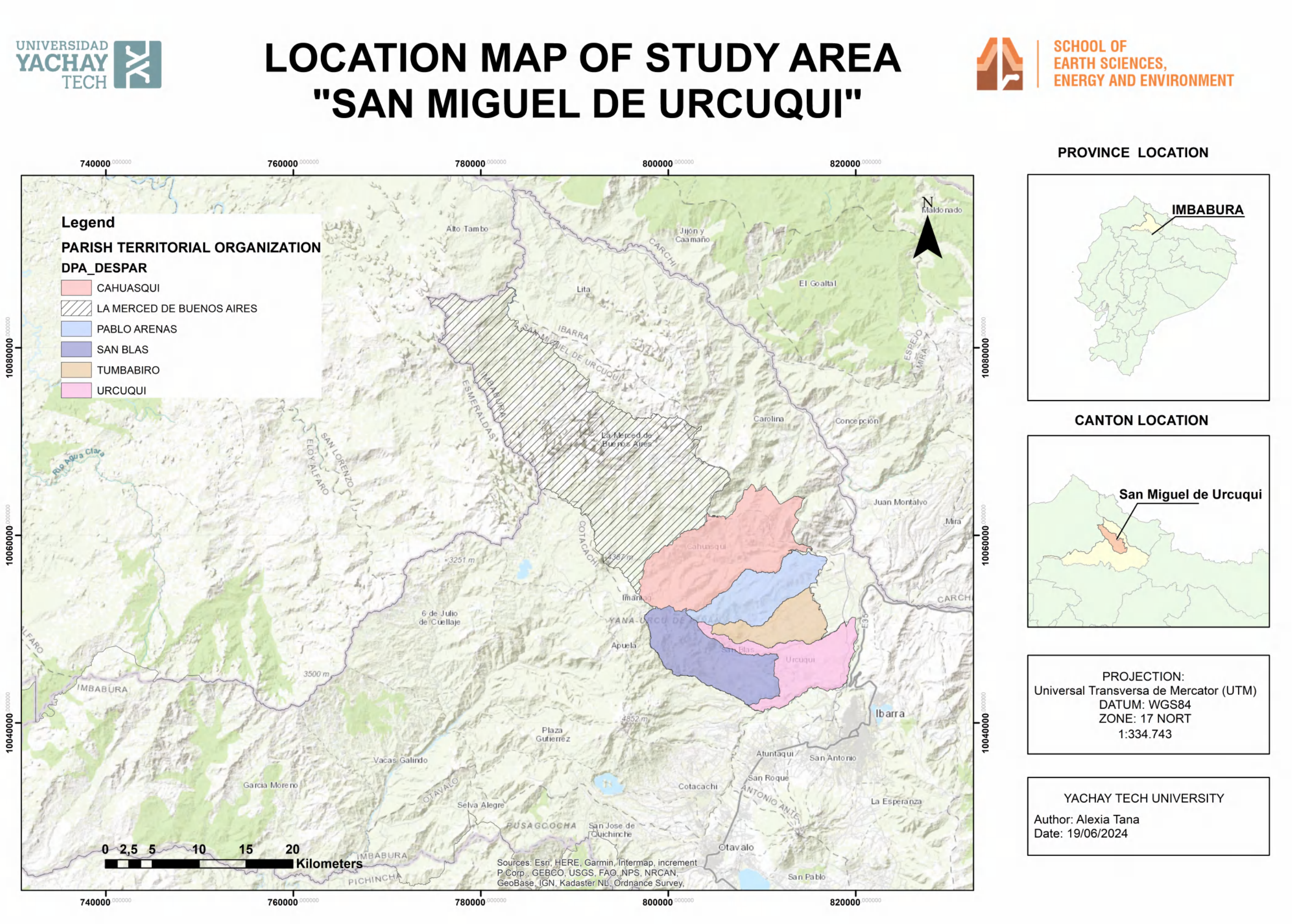


Figure 1. Study area location, showing San Miguel de Urcuqui, the Imbabura Province, North part of Ecuador.

context, including paramo ecosystem protection, environmental restrictions, land use conflicts, and integration with smallholder agricultural systems. In this way, it supports the country's energy diversification and decentralization goals.

3 Methodology

3.1 Study Area

Located at 0°31'N 78°12'W, at 2295 m a.s.l the study area of this research is the canton of Urcuqui, which is located in the province of Imbabura in northern Ecuador and is divided into 6 divisions at the parish level. The canton occupies an area of more than 779 square kilometers and has a population of 17969 inhabitants (2022) with a projection of 19060 by 2025. Urcuqui has experienced a considerable increase in the last decade, with a growth rate of 8.46%. Solar, wind, and other forms of renewable energy are in a very early stage of development in Urcuqui, with only pre-feasibility studies. About 70% of the energy consumed comes from outside Urcuqui and corresponds to renewable energy from the main hydroelectric power plants that supply Ecuador [34]. This study covers five parishes from San Miguel de Urcuqui canton: Urcuqui, San Blas, Tumbabiro, Pablo Arenas, and Cahuasqui (Figure 1), which consist of a 315.62 km² geographical area. Buenos Aires Parish is excluded of this research due to illegal mining.

3.1.1 *Hydrology and Climate*

The canton of Urcuqui has a remarkable climatic diversity, ranging from dry conditions in the southeast to humid and páramo climates in the north and northeast, respectively. The average annual temperature ranges from 13.90 °C to 24 °C. Rainfall varies greatly, ranging from 200 mm in arid areas to 3,100 mm in the highlands of the western part of the canton, where rainforests are located. These climatic parameters are strongly influenced by the mountainous topography, the presence of the Chota Valley, and the proximity to the jungle in the north [34]. This climatic diversity supports considerable water resources, characterized by multiple rivers and streams. The canton is located within the Mira River basin and is drained by tributaries such as the Pisangacho stream in the eastern part and the San Rafael and Coñaqui streams in the western part. Among its main rivers are the Lita, Verde, Ambi, and Palacara, whose flows are used for irrigation, agriculture, and livestock [35].

3.1.2 *Protected Areas*

The Cotacaqui Cayapas National Park has an extension of 2,436.38 km². In Urcuqui, 61.76 km² are located in the canton, distributed in the eastern part of the canton. The main areas are located in the Buenos Aires parish (40%), then Cahuasqui (31.6%), San Blas (24.9%), Pablo Arenas (2.7%) and Urcuqui (0.2%). Tumbabiro parish contains no protected areas.

3.2 Methodological Framework

This study presents a comprehensive assessment of the solar energy potential in San Miguel de Urcuqui, Ecuador, through an integrative methodology that combines geospatial analysis with field validation. The research employs a multi-criteria decision-analysis (MCDA) framework within a Geographic Information System (GIS) environment, supported by remote sensing data, to identify optimal sites for solar energy deployment. The systematic framework, illustrated in Figure 2 comprises four phases: (1) Data Acquisition, (2) Resource Potential Analysis, (3) GIS-Based Suitability Mapping, and (4) Ground Validation. This approach ensures a complete evaluation that balances technical viability with economic, environmental, and social considerations.

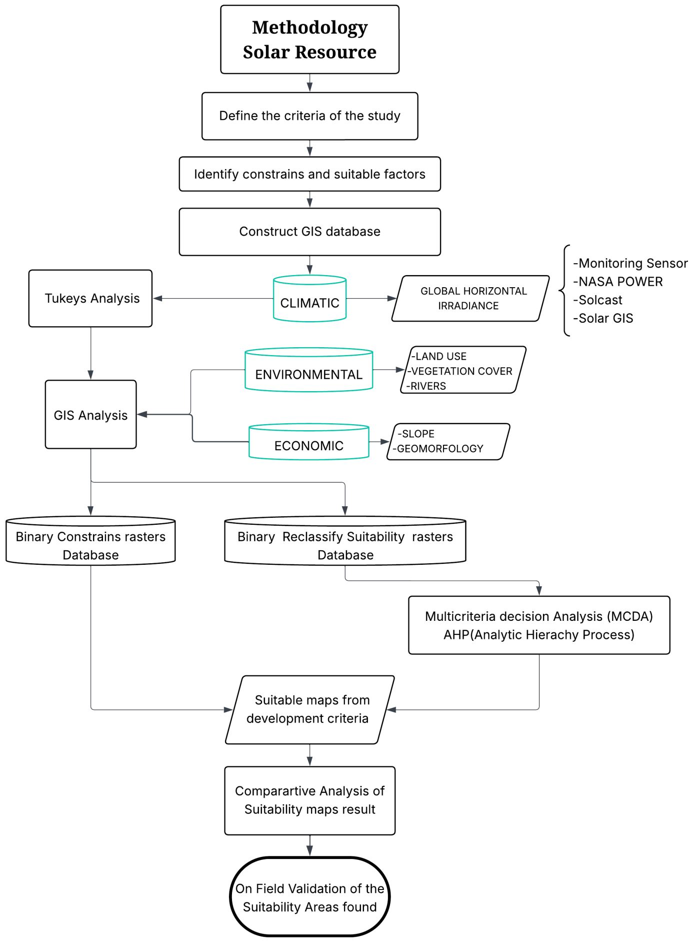


Figure 2. Scheme of the steps that comprise this research

3.3 Criteria Selection and Data Acquisition

To identify optimal sites, it is essential to establish relevant spatial criteria. The specific criteria were derived from the data sources in Table 3. This dataset includes a Digital Elevation Model (DEM) for topographic criteria, satellite-derived and ground-measured solar irradiation (GHI) data for energy potential, and thematic cartography for land-use constraints. As the most recent comprehensive data available, the period 2014–2023 was used. From these data sources, three primary suitability criteria were established: climatic, economic, and environmental. The subsequent analysis involved preparing this dataset, conducting a variability assessment, and applying a weighted overlay to integrate the criteria and determine site suitability.

Table 3. Main data sources used in the investigation.

Dataset	Data Type	Source
DEM Urcuqui	Digital Elevation Model (DEM)	[47]
Irradiation (GHI)	Satellite-Derived Data	[48], [42], [51]
	Ground-Based Measurements	Environmental monitoring sensor
Thematic cartography Urcuqui	Geospatial Polygon Data (GPI)	[43]

3.3.1 *Climatic criteria*

This research utilized Global Horizontal Irradiance (GHI) as the primary climatic criterion (Figure 3(b)). GHI is a fundamental parameter for assessing solar energy potential, as it quantifies the total solar radiation incident on a horizontal surface. Consequently, identifying locations with optimal GHI values is essential for the deployment of efficient and productive renewable energy systems, making this parameter a cornerstone of the present study [36].

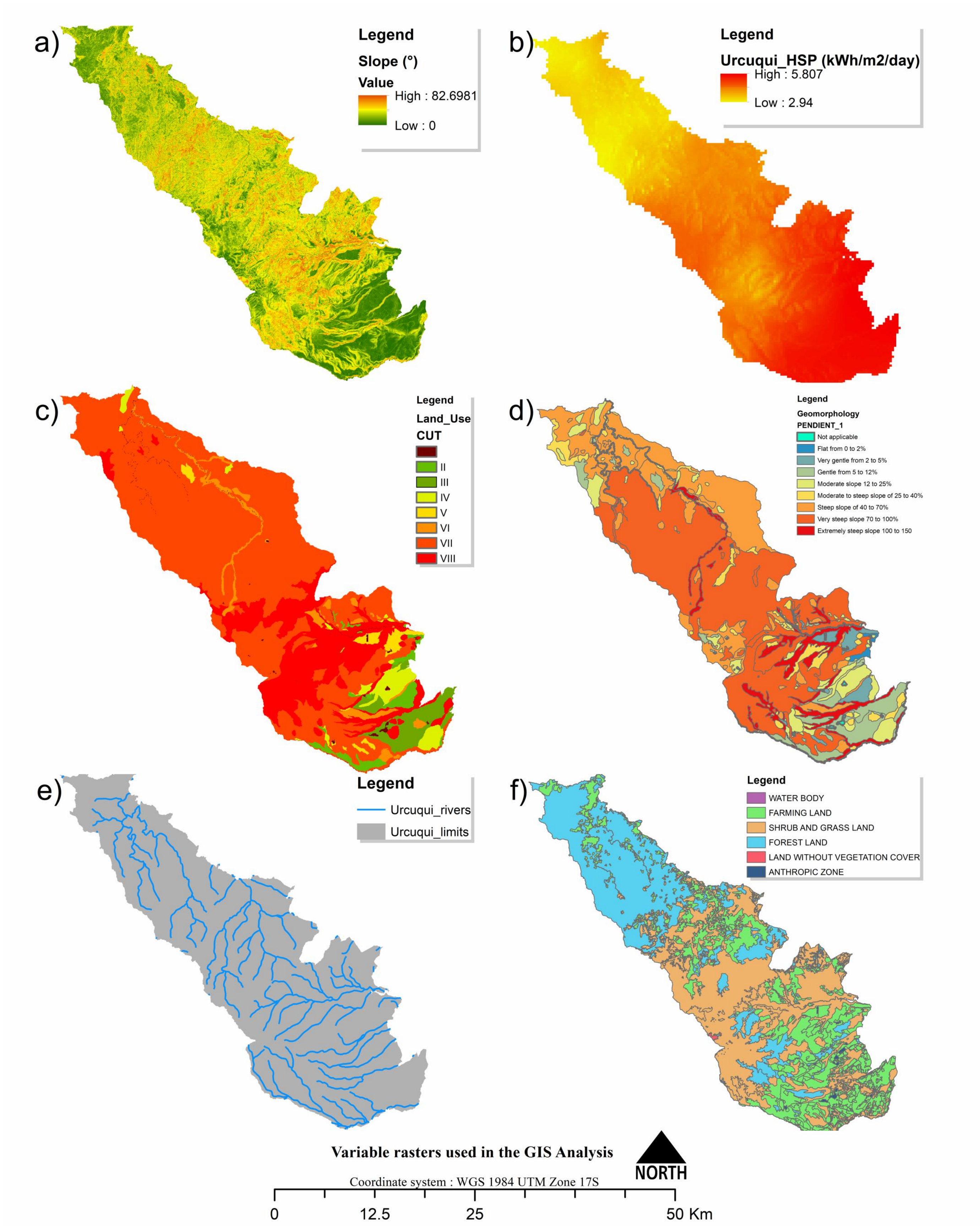


Figure 3. Parameters used in the analysis of Solar suitability.

3.3.2 *Environmental criteria*

The environmental criteria selected for this research were vegetation cover, rivers, and land use for solar plants exclusion (Figure 3(c,e,f)). To install a power system, the protected areas need to be excluded to reduce any possible damage to the environment, and the river exclusion ensures the protection of water resources and streams [37].

3.3.3 *Economic criteria*

The economic criteria selected for this research were the geomorphology and slope (Figure 3(a,d)). The accessibility to the power lines infrastructure and roads reduces the operational costs of installing a power system. The slope is one of the factors that determines the location of a solar power plant. High grades of terrain inclination increase the cost of implementing PV systems [38].

3.4 Data Analysis

To evaluate the suitability of Urcuqui, statistical analyses were established based on the available information to evaluate the seasonal variability of solar resources.

3.4.1 *Tukey's Analysis*

Tukey's Test is a statistical method used to perform multiple pairwise comparisons of means, allowing comparing the differences in medians and temporal series, useful to predict the trend in the next years [39]. In this study, the Tukey test was applied to evaluate the variability of irradiance between the five parishes of Urcuqui, using the PSH means obtained from NASA Power Data from 2010 to 2024.

3.4.2 *GIS Analysis*

Following the assessment of general resource suitability, the next critical step was to identify and exclude unsuitable areas based on specific technical and environmental constraints. This was achieved by applying a set of exclusion criteria, evaluated through a binary system where 0 represents excluded areas and 1 represents viable locations. The rationale for these criteria and their specific thresholds, summarized in Table 4, was derived from the optimal conditions for photovoltaic system implementation, as established in the literature [28, 40, 41].

The selected parameters ensure a holistic evaluation across climatic, economic, and environmental dimensions. For instance, a solar irradiance threshold of $> 4.5\,\text{kWh/m}^2\text{/day}$ guarantees a minimum energy yield, while a slope limit of

Table 4. Parameters for photovoltaic system site selection.

Parameter	Optimal Range	Suitability (0,1)	Data Sources
Solar Irradiance	>4.5 kWh/m²/day	1: >4.5 kWh/m²/day 0: <.4.5 kWh/m²/day	[42]
Slope	<15°	1: <15° 0: >15°	[43]
Land Use	I y II	1: I y II 0: III-VIII	[43]
Geomorphology	Low Relief	1: Low Relief 0: High Relief	[43]
Rivers	50 m buffer	1: >50 m buffer 0: <50 m buffer	[43]
Vegetation cover	Herval and shrub vegetation	1: Herbaceous and shrub 0:Protected forests and crops	[43]

$< 15°$ minimizes earthworks and construction costs. Land use and vegetation cover criteria prioritize non-protected, low-value vegetation: Classes I & II (herbaceous vegetation, shrubland, barren soil) to avoid environmental conflict and high land costs.

The exclusion of protected areas, forests, ravines(Classes III-VIII), and river buffers (50 m for rivers) is mandated to prevent habitat fragmentation, soil erosion, watercourse sedimentation, and biodiversity loss. Furthermore, a favorable geomorphology (low relief) significantly reduces infrastructure and development expenses.

To operationalize this analysis within the GIS, each corresponding data layer was processed using the Reclassify tool in ArcMap 10.8. Spatial resolution was harmonized to a common 12m grid via bilinear resampling for all layers except GHI (150m retained for accuracy). Data analysis for GHI involved cross-validation tendency analysis between satellite and ground data, ensuring reliability. Ground measurements filled temporal gaps in satellite data. This standardized set of rasters was then capable of being combined through a weighted overlay to produce a final integrated suitability map that combines all exclusionary factors.

3.4.3 *Multicriteria decision Analysis(MCDA)*

MCDA is a well-established methodology for identifying optimal sites for solar installations [31, 32]. To apply MCDA, each parameter was evaluated based on solar suitability criteria and energy system requirements using the Analytic Hierachy process (AHP) [28].

3.4.4 *Analytic Hierachi Process*

The AHP is a widely used methodology for identifying suitable sites for renewable energy projects, as shown in Table 2. The AHP method, developed by [44], is a structured technique for organizing and analyzing complex decisions. It is based on a pairwise comparison matrix, which codes the importance of each factor compared to the others (Table 5).

Table 5. Scale for the entries in the comparison matrix [28].

Scale	Degree of Importance
1	Equally important
2	Equally to moderately important
3	Moderately important
4	Moderately to strongly important
5	Strongly important
6	Strongly to very strongly important
7	Very strongly important
8	Very strongly to extremely important
9	Extremely important

Once the priority criteria were established, a pairwise comparison matrix will be generated with (n x n) dimensions (Table 6).

Table 6. Pairwise comparison of main criteria.

	A	B	C
A	1	a	b
B	1/a	1	c
C	1/b	1/c	1

Consistency Check: To verify that the comparisons don't have contradictions, the autovalues of the matrix, the consistency index (CI), and the consistency ratio (CR) are calculated.
The Consistency Ratio (CR) is calculated as:

$$CR = \frac{CI}{RI} \tag{1}$$

where the Consistency Index (CI) is given by:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

with:

$\lambda_{\max}$ = Principal eigenvalue of the comparison matrix
n = Number of criteria
RI = Random Index (reference value)

3.4.5 *Weight Calculations*

In the process of ranking criteria using MCDA, there are several methods for weighting layer criteria. For this research, the standardized binary subcriteria layers from GIS Analysis were combined using the weights from the AHP process.

Eigenvalue Calculation

For each parameter, the eigenvalue is calculated as:

$$Eigenvalue = \sqrt[n]{\prod_{i=1}^{n} a_{ij}} \tag{3}$$

where:

n = Number of criteria

a_{ij} = Element in row i, column j of the pairwise comparison matrix

$\prod$ = Product operator for all elements in the row

Note: This geometric mean method ensures equal weighting of all comparisons in the row.

3.4.6 *Normalized Weights*

The next step is to obtain the weight for each criteria i that is calculated as:

$$\text{Weight}_i = \frac{\text{Eigenvalue}_i}{\sum_{j=1}^{n} \text{Eigenvalue}_j} \tag{4}$$

where:

Eigenvalue_i = Geometric mean of row i
n = Total number of criteria
$\sum_{j=1}^{n} \text{Eigenvalue}_j$ = Sum of all eigenvalues in the matrix

Properties

To verify that the obtained values are correct, the following conditions must be satisfied

$$0 \leq \text{Weight}_i \leq 1$$
$$\sum_{i=1}^{n} \text{Weight}_i = 1$$

3.4.7 Photovoltaic Potential Indicator

Applying all the obtained weights for each parameter, the weight overlay can be generated with the use of Raster Calculator GIS tools, following the equation (5) to finally obtain a raster map showing a scale of suitability related to the number of cells matched.

$$PI = \sum_{i=1}^{n} (W_i \times X_i) \tag{5}$$

where:

PI = Photovoltaic potential Indicator
W_i = AHP-derived weight
X_i = Normalized value (0,1) of criterion i
n = (total criteria)

3.5 Energy Potential Analysis

3.5.1 PV Potential

PV potential represents the expected lifetime average electricity production for a PV system at a specific location. Calculating the photovoltaic (PV) potential involves estimating how much energy can be generated based on GHI values, environmental factors, and the efficiency of solar panels.

The theoretical annual energy generation capacity was calculated by equation (6) where:

$$E_{PV} = \underbrace{A}_{\substack{\text{Area}\\(\text{km}^2)}} \times \underbrace{\rho_{\text{install}}}_{\substack{\text{Installation}\\\text{Density}\\(10\ \text{MW/km}^2)}} \times \underbrace{f}_{\substack{\text{Usable}\\\text{area}\\\text{factor}}} \times \underbrace{H_{\text{peak}}}_{\substack{\text{Peak sun}\\\text{hours}\\(\text{kWh/m2/day})}} \times (365/1000) \tag{6}$$

where:

E_{PV} = Annual PV energy generation (GWh)
A = Suitable area from GIS analysis (km²)
ρ_{install} = Installation density (10 MW/km²)
f = Usable area factor (0.85 for access roads)
H_{peak} = Peak sun hours per day (4.5 h Urcuqui)
365 = Days of operation per year

4 Results

4.1 Solar Energy Resources in San Miguel de Urcuqui Canton

4.1.1 Solar Seasonal Variability

Analyzing seasonal variations in irradiation is crucial for evaluating PV feasibility and planning for power grid management. Figure 4 displays the monthly PSH from 2001 to 2024, revealing a reduction in season length. Since 2015, the values have stayed high, with only a brief rainy season, resulting in a prolonged dry season.

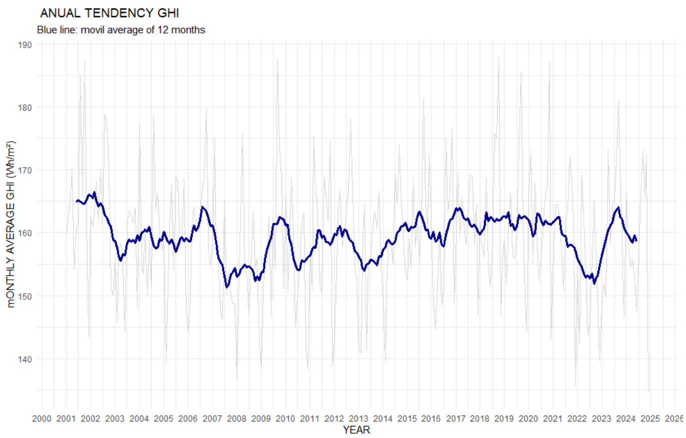


Figure 4. Hourly solar radiation data from 2001 to 2024 [48].

To establish a reliable solar energy baseline for the Urcuquí canton, historical data from the NASA Power database was analyzed across its urban and rural parishes. A statistical Tukey's test was performed at a 95% confidence level to identify significant differences in Peak Sun Hours (PSH). The results, shown in Figure 5 and Table 7, reveal distinct solar potential groupings.The analysis indicates that the parishes can be categorized into two statistically significant groups. The first and most favorable group consists of Urcuquí, Tumbabiro, and San Blas. Urcuquí parish reaches the highest mean PSH value of 4.04 kWh/m²/day, while Tumbabiro and San Blas show a similar, high potential of 4.55 kWh/m²/day, indicating no significant variability within this group. The second group, comprising Pablo Arenas and Cahuasqui, presents a lower mean PSH of 4.25 kWh/m²/day, representing areas with comparatively less solar resources.

Following this spatial analysis, the accuracy of the satellite-derived data was verified against ground measurements. As demonstrated in Figure 6, the Global Horizontal Irradiance (GHI) from NASA Power, Solcast, and a local monitoring sensor for the year 2024 is compared. The comparison reveals

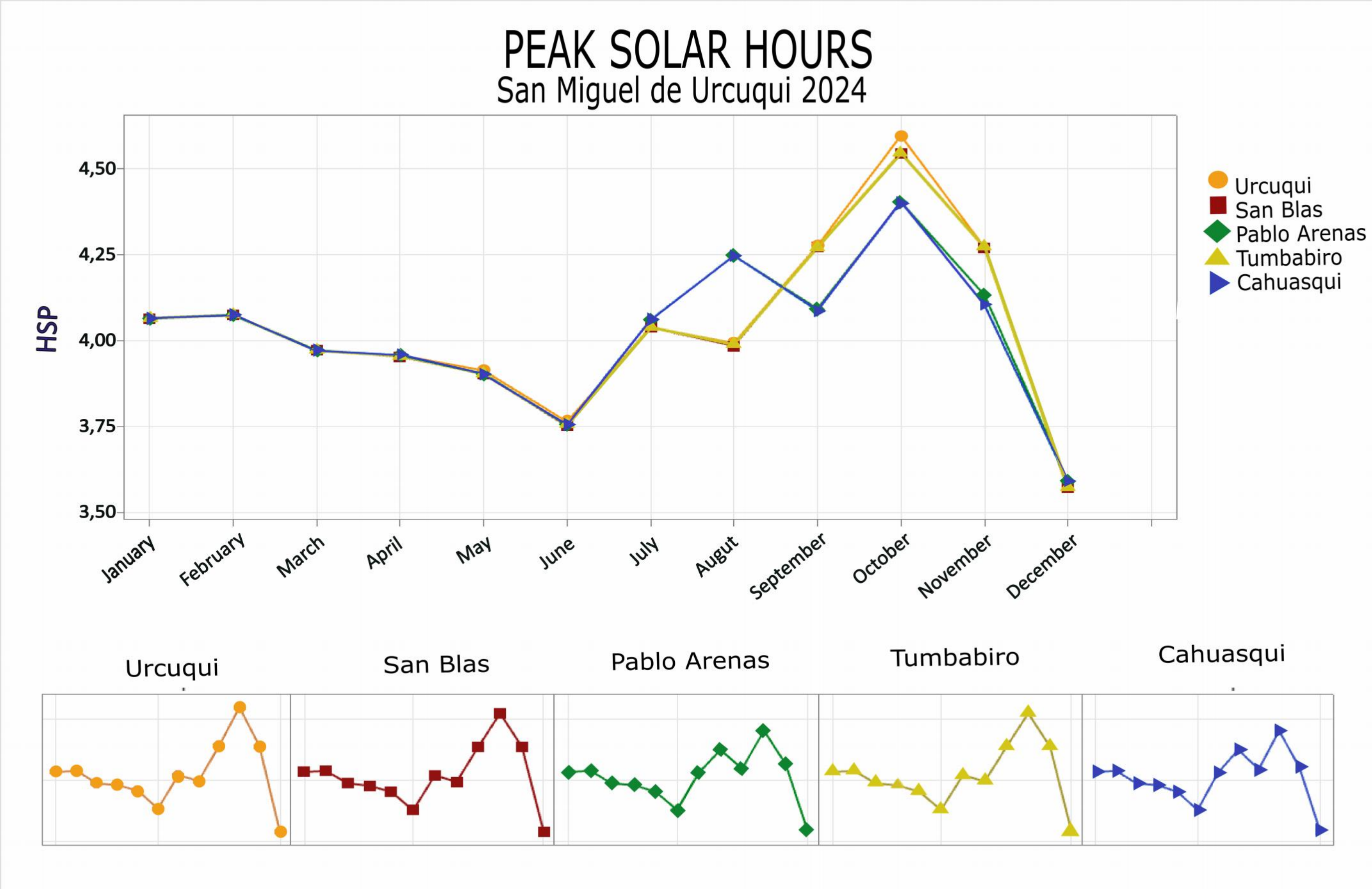


Figure 5. Comparison of monthly peak solar hours (PSH) between the parishes of Urcuqui, Tumbabiro, Cahuasqui, and Pablo Arenas.

Table 7. Tukey's test results for PSH across the parishes of Urcuquí canton, 2024.

Factor	N	Mean	Std. Dev.	95% CI
Urcuqui	13	4.0411	0.2489	(3.9032; 4.1790)
San Blas	13	4.0335	0.2415	(3.8956; 4.1714)
Tumbabiro	13	4.0343	0.2410	(3.8964; 4.1723)
Pablo Arenas	13	4.0211	0.2034	(3.8831; 4.1590)
Cahuasqui	13	4.0183	0.2021	(3.8803; 4.1562)

Note: Pooled standard deviation = 0.238434.

consistent seasonal trends across all datasets for which data is available, with October exhibiting the peak in solar radiation. Despite the absence of ground sensor data for January, May, June and July, a subsequent quantitative data fusion and cross-validation analysis yielded critical insights. While the datasets demonstrated strong visual agreement, advanced fusion methodologies revealed significant enhancement in accuracy when combining sources.

As demonstrated in Table 8, machine learning-based fusion yielded a 60.7% enhancement in accuracy, as evidenced by a reduction in root mean square error (RMSE) to 0.097. This improvement was achieved across all individual datasets, with the sensor data alone demonstrating exceptional reliability (RMSE: 0.247) and satellite sources exhibiting complementary biases that underwent enhancement upon combination. This robust validation and demonstrated enhancement of accuracy serve to confirm the reliability of these combined datasets for the subsequent analysis of their suitability.

4.2 Scenario Definition and AHP Configuration

This study evaluates site suitability under three distinct decision-making scenarios to understand how different priorities affect the outcome. Each scenario is defined by a specific preference structure among the three main criteria: Climatic, Economic, and Environmental. The scenarios are as follows:

1. **Economic Priority:** Maximizes economic feasibility, where climatic potential is a critical enabler and environmental impact is a limiting factor.
2. **Environmental Priority:** Maximizes environmental protection, with economic

and climatic factors serving as secondary constraints.

3. **Balanced Priority:** Strikes an even balance, weighting environmental, economic, and climatic factors equally.

4.2.1 *Criteria Weights and Consistency Validation*

A pairwise comparison matrix was constructed for each scenario. The Analytic Hierarchy Process (AHP) was applied to calculate the corresponding criterion weights, and the consistency of each judgment was verified, with all Consistency Ratios (CR) being well below the threshold of 0.1. Within Table 9, the systematically calculated weights for the primary criteria across all three scenarios are systematically summarized, and in (Table 10), the precision of these weights is corroborated. Furthermore, a sensitivity analysis was conducted by varying each criterion's weight by ±15%. Results indicate that solar irradiance (GHI) and slope are the most influential factors, causing up to ±32% change in suitable area. The analysis revealed that land use and distance to rivers exhibited a moderate influence, with a standard deviation of approximately 12%. In contrast, geomorphology and vegetation cover demonstrated a lower impact, with a standard deviation of around 7%. This finding serves to underscore the robustness of the AHP weighting, while simultaneously highlighting the necessity for precise data accuracy in specific domains.Following the assignment of weights to the main criteria, the subsequent phase involved allocating the final weights to the sub-criteria. These weights constitute an essential component of the foundational framework for the subsequent weighted overlay analysis executed within the Geographic Information System (GIS).

4.2.2 *Final Weighted Hierarchy by Scenario*

The hierarchical weights for all parameters were finalized by distributing the weight of each main criterion (from Table 9) among its respective sub-criteria. This distribution was performed using pairwise comparisons consistent with the logic of each scenario, ensuring that the internal priorities of the Climatic, Economic, and Environmental criteria reflected the overarching goal of the scenario. The resulting comprehensive weights for all scenarios are presented in Tables 11, 12, and 13.

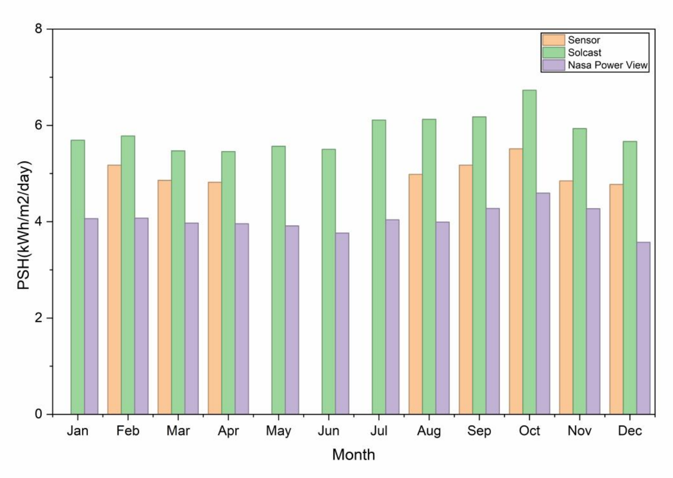


Figure 6. Comparison of average monthly solar radiation (GHI) datasets for Urcuqui parish in 2024, showing the correlation between satellite-derived data (NASA, Solcast) and ground-based sensor measurements.

In the **Economic Priority** scenario (Table 11), the high weight of the Climatic criterion (0.547) is allocated entirely to Solar Irradiance (GHI), establishing it as the single most important parameter. Within the Economic criterion, Slope receives the dominant share due to its direct impact on construction costs. The Environmental parameters collectively have a minimal influence, as expected in a cost-driven scenario.

In the case of the **Environmental Priority**, the scenario (Table 12) demonstrates a strong emphasis on conservation. The Environmental criterion's weight (0.659) is distributed among its sub-criteria, with Land Use and Vegetation Cover receiving the highest priority to avoid ecological conflicts. In this context, the economic and climatic factors are significantly downweighted, acting primarily as constraints rather than drivers.

The **Balanced Weight** scenario achieves its objective by assigning equal weight (0.333) to each main criterion, which is then proportionally allocated to its respective sub-criteria (Table 13).

4.2.3 *Resulting binary subcriteria Layers*

To transition from the AHP-derived priorities into a spatial model, all input datasets were reclassified into binary suitability layers. Figure 7 presents a series of binary rasters resulting from the Geographic Information System (GIS) reclassification process for identifying suitable sites for solar farms. Each layer has been standardized to a common suitability scale, where 1 (typically shown in green color) represents "suitable" or "feasible" areas and 0 (shown in dark

Table 8. Quantitative accuracy assessment through data fusion.

Data Source	Method	RMSE (kWh/m²)	MAE (kWh/m²)	Bias (kWh/m²)	Accuracy Improvement
Fusion Methods:	ML Fusion	**0.097**	**0.072**	-0.017	**+60.7%**
	Weighted Fusion	0.246	0.238	-0.238	+0.3%
Individual Sources:	Ground Sensor	0.247	0.178	+0.012	—
	Solcast	0.910	0.871	+0.871	-268.4%
	NASA Power	0.903	0.888	-0.888	-265.6%

Abbreviations: RMSE = Root Mean Square Error, MAE = Mean Absolute Error (both in kWh/m², lower is better). Bias = systematic error tendency. Improvement = RMSE reduction versus best single source. ML = Machine Learning.

Table 9. Final main criterion weights for the three decision -making scenarios.

Criterion	Economic Priority	Environmental Priority	Balanced Weight
Climatic	0.547	0.131	0.333
Economic	0.333	0.210	0.333
Environmental	0.120	0.659	0.333

Table 10. Summary of Consistency Ratios for all scenarios.

Scenario	Consistency Ratio (CR)
Economic Priority	0.016
Environmental Priority	0.022
Balanced Weight	0.000

Note: All CR values < 0.1, confirming acceptable consistency.

Table 11. Final parameter weights for the **Economic Priority** scenario.

Criterion	Parameter	Weight
Climatic (0.547)	GHI	0.547
Economic (0.333)	Slope	0.250
	Geomorphology	0.083
Environmental (0.120)	Land Use	0.060
	Distance to Rivers	0.040
	Vegetation Cover	0.020

Table 12. Final parameter weights for the **Environmental Priority** scenario.

Criterion	Parameter	Weight
Climatic (0.131)	GHI	0.131
Economic (0.210)	Slope	0.155
	Geomorphology	0.055
Environmental (0.659)	Land Use	0.278
	Distance to Rivers	0.180
	Vegetation Cover	0.201

Table 13. Final parameter weights for the **Balanced Weight** scenario.

Criterion	Parameter	Weight
Climatic (0.333)	GHI	0.333
Economic (0.333)	Slope	0.222
	Geomorphology	0.111
Environmental (0.333)	Land Use	0.167
	Distance to Rivers	0.111
	Vegetation Cover	0.055

color) represents "excluded" or "non-favorable" areas, based on specific exclusion criteria. The reclassification of criteria established clear thresholds for site exclusion across six parameters. To ensure economic feasibility, slopes exceeding 15% were excluded due to increased construction costs and engineering complexities, while solar resource availability was guaranteed by mandating a minimum of 4.5 kWh/m²/day of Peak Sun Hours (PSH). Land use is categorized quantitatively based on ecological value and development conflict. Land suitability is the primary factor in this assessment. Categories I–III (areas with low environmental restrictions) are characterized by low ecological sensitivity and low agricultural economic value. This makes them highly suitable for solar development while minimizing land acquisition costs and socio-environmental displacement. Categories IV–X (areas with high environmental restrictions) are excluded due to their high ecological value and legal protections. This integrated approach ensures that site selection prioritizes already-disturbed or low-productivity lands, thereby reducing both financial outlay and environmental conflict. The analysis also selected low-relief geomorphology over high-relief terrain to simplify construction. Solar installations in

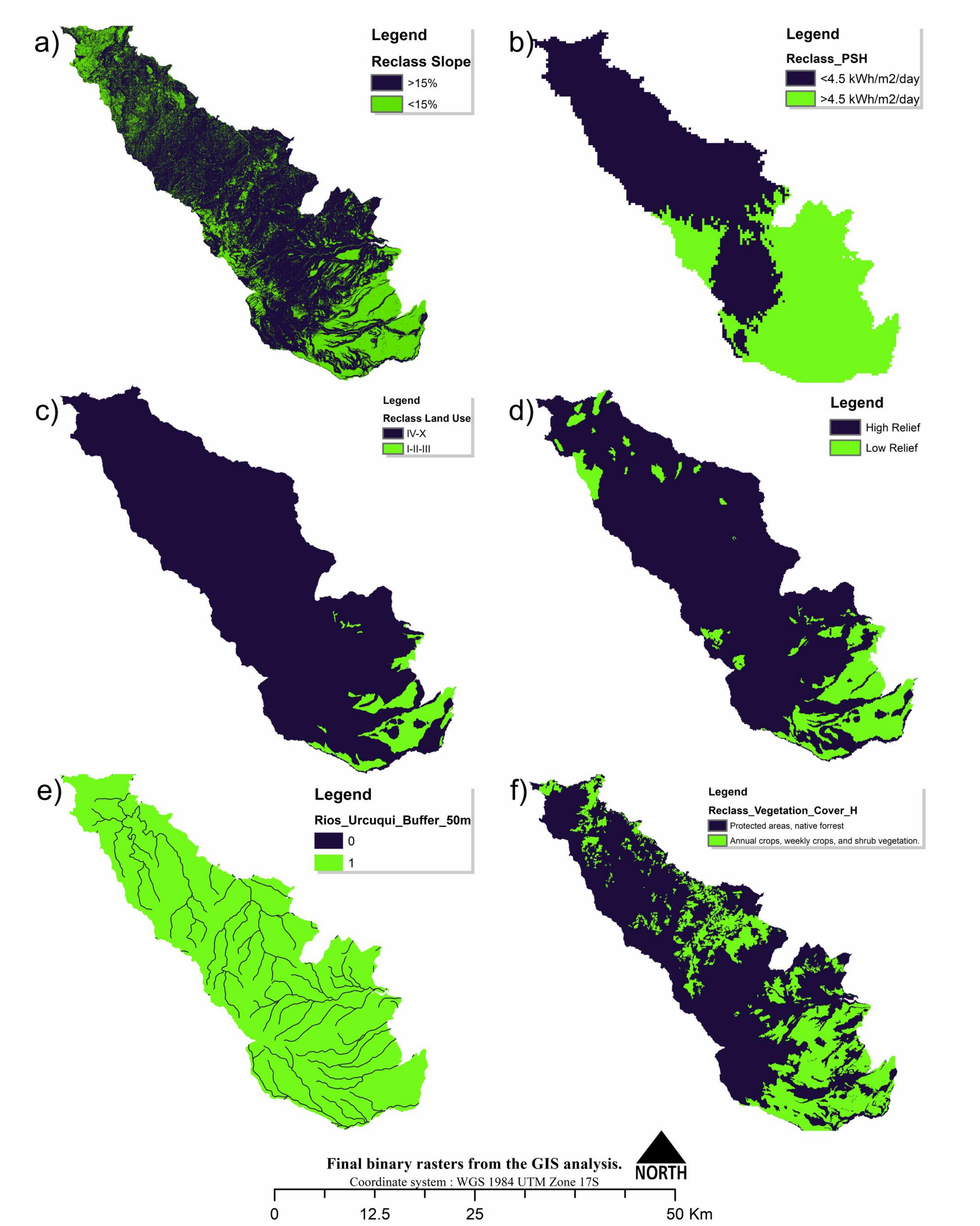
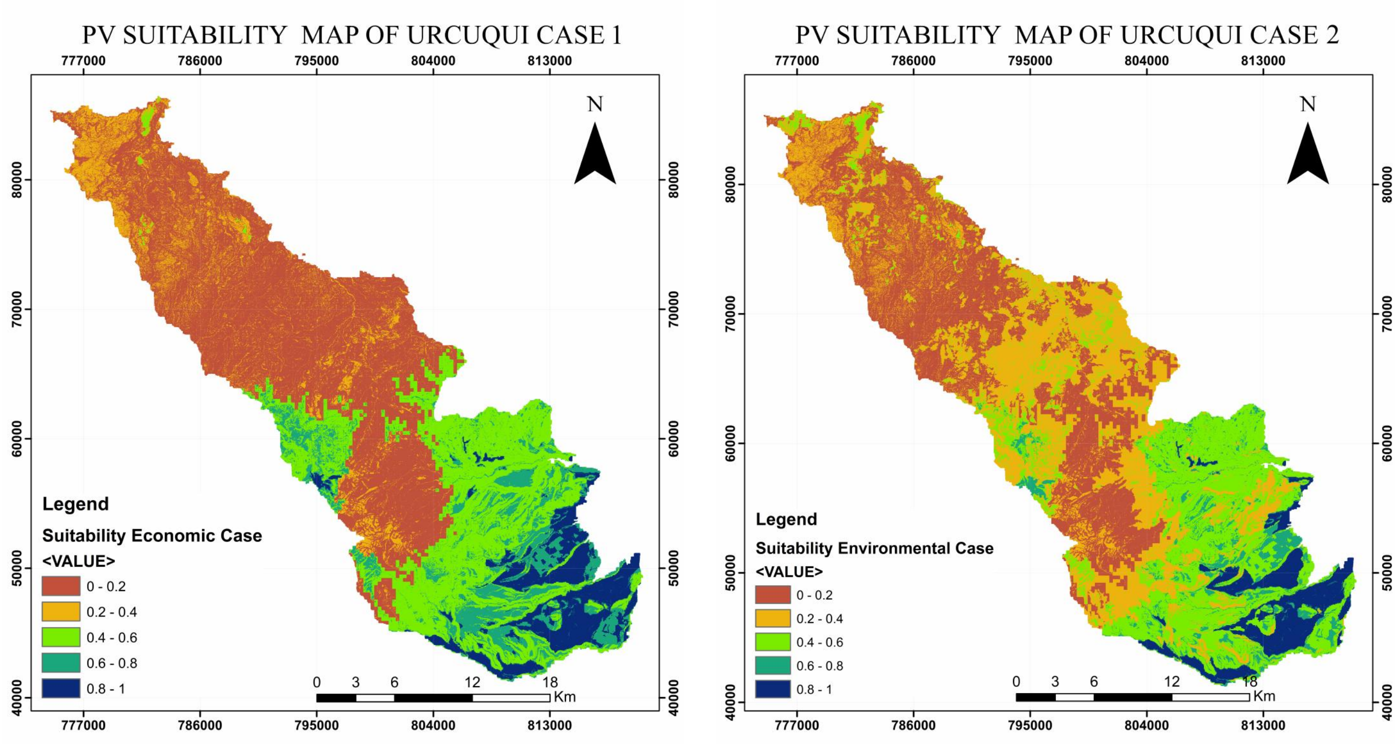


Figure 7. Reclasification binary result of the GIS analysis.



(a) Economic Priority (b) Environmental Priority

Figure 8. Comparative analysis of solar suitability maps: (a) Economic Priority scenario and (b) Environmental Priority scenario.

high-altitude ecosystems are strictly excluded due to their critical role in water regulation and carbon sequestration. From an environmental perspective, the model categorically protected sensitive ecosystems by excluding native forests, rivers, and protected areas, allowing development only in areas with herbaceous or shrub vegetation.

4.3 Final Suitability Maps

The final AHP weights for each scenario were applied through a weighted overlay analysis in GIS, generating three distinct suitability maps for solar power plant development in the canton of San Miguel de Urcuquí. The resulting suitability for every location is categorized into five levels: **Very High** (0.9–1), **High** (0.7–0.9), **Medium** (0.5–0.7), **Low** (0.3–0.5), and **Unsuitable** (0–0.3).The spatial distribution of suitable areas varies significantly based on the prioritization criteria, as shown in Figures 8 and 9.

- **Economic Priority Scenario (Figure 8(a)):** This scenario reveals the most extensive areas of high and very high suitability, predominantly concentrated in the southwestern parishes of Urcuquí and Tumbabiro. The model prioritizes low-slope terrain and proximity to infrastructure, leading to a more permissive selection that maximizes potentially developable land.

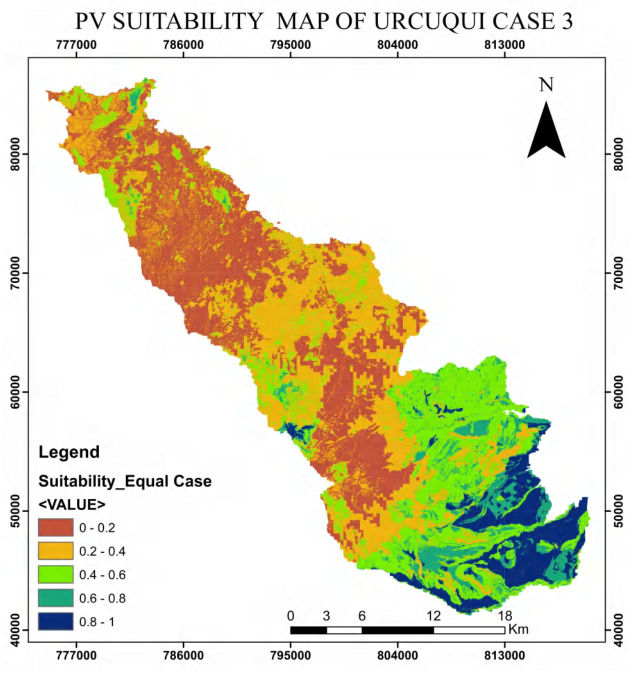


Figure 9. Solar suitability map for the Balanced Weight scenario.

- **Environmental Priority Scenario (Figure 8(b)):** In contrast, this scenario shows the most restrictive pattern. High and very high suitability zones are scarce and fragmented, as the model heavily weights protected areas, forests, and specific land-use classes as exclusionary. The most suitable pockets are confined to pre-existing low-impact vegetation zones in Urcuqui, Tumbabiro, and San Blas, while large swathes of the canton, particularly in the north (Pablo Arenas, Cahuasquí) and east, are deemed unsuitable.

- **Balanced Weight Scenario (Figure 9):** This scenario presents a compromise, with a moderate distribution of suitable areas. It identifies viable areas of medium to high suitability stretching through the southeast region, encompassing parts of Urcuquí, Tumbabiro, and San Blas. This result effectively balances the solar potential and economic drivers of the Economic scenario with the conservation constraints of the Environmental scenario.

Across all scenarios, the central and northern parishes of Pablo Arenas and Cahuasquí consistently show low suitability due to a combination of challenging topography and environmental restrictions. The northwestern Buenos Aires parish remains largely unsuitable in every model, confirming its role as a critical zone for conservation.

4.4 Energy Generation Capacity

The comprehensive photovoltaic potential assessment, detailed in Table 14, reveals substantial energy generation capacity across the canton. The total suitable area of 35.64 km^2 translates to an installable capacity of 356.4 MW, capable of generating approximately 585.59 GWh/year. This energy output could potentially power 146,398 households, assuming an average consumption of 4 MWh per home annually [45]. The distribution of this potential exhibits strong spatial heterogeneity, with Urcuqui parish alone contributing 42.5% of the total capacity (151.4 MW), underscoring its strategic importance for regional solar energy development.

4.5 Strategic Implications and Regional Impact

The concentration of photovoltaic potential in Urcuqui, Tumbabiro, and San Blas parishes suggests strategic prioritization for solar energy development initiatives. These areas not only offer substantial generation capacity but also benefit from proximity to existing infrastructure, potentially reducing implementation costs and improving grid integration feasibility. The identified potential of 585.59 GWh/year represents approximately 15% of Imbabura Province's current electricity consumption [46], highlighting the significant contribution this development could make to regional energy security and renewable energy targets.

The methodological approach employed—combining multi-criteria decision analysis with geospatial assessment—provides a robust framework for renewable energy planning that can be replicated in similar Andean regions. The results demonstrate that careful site selection considering both technical potential and sustainability criteria can identify substantial renewable energy resources while minimizing environmental impacts and maximizing socioeconomic benefits.

4.6 Energy generation potential

Using the Equation 5, the total area available for solar panels (Figure 10) was calculated and compared per parish. Table 14 shows Urcuqui as the parish with the largest area for PV systems, with 25% of available area, followed by Tumbabiro and San Blas with 15% and 7% respectively. To calculate the photovoltaic potential the suitable area used was followed the equal weight case.

4.6.1 Power Capacity Projection and System Design

Based on the suitable areas identified, we project the installable capacity

Assuming 4 MWh per home per year as the average energy consumption, it illustrates the equivalent number of homes powered by parishes Table 14, showing its contribution to the country's energy system.

5 Discussion

5.1 Variability of Solar radiation (GHI) in Urcuqui

Ecuador, located on the equatorial line or parallel 0, has only two seasons: summer (dry season) and winter (rainy season). The dry season spans from July to November, with predominantly sunny days. December, January and March are transitional months leading into the rainy season; during this period, the climate is moderately humid with both rainfalls and sunny days. The winter or rainy season runs from April to June, characterized by increased rainfall and cloudy days. Also, prolonged dry season (July–December) yields high, stable GHI (5.2 kWh/m²/day), maximizing PV output and grid stability. The rainy

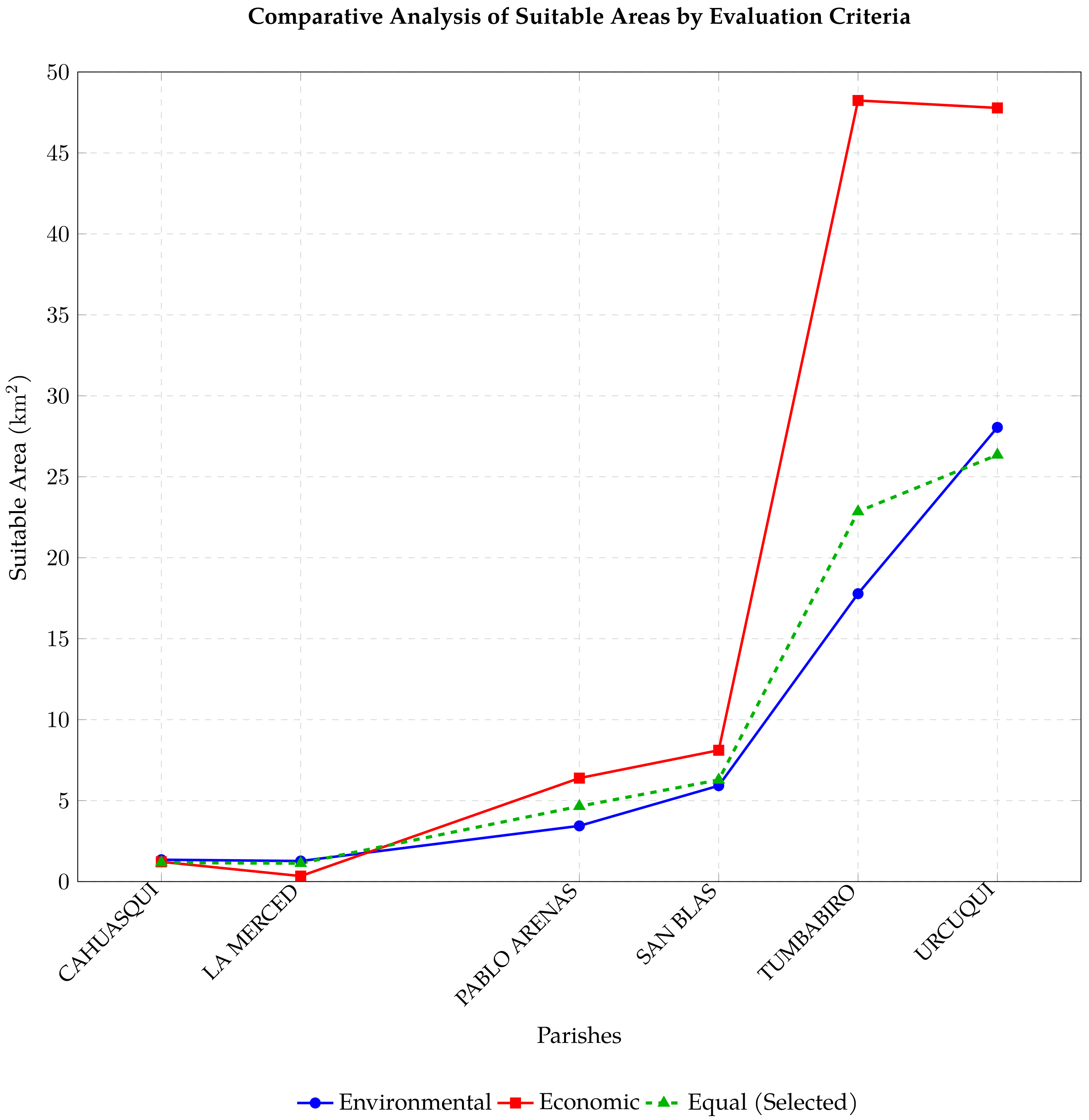


Figure 10. Comparative trend of suitable areas for photovoltaic installation according to different multi-criteria evaluation approaches. The equal-weighting scenario (green dashed line) was selected for photovoltaic potential assessment, as it balances environmental and economic considerations. Notable variations are observed across parishes, with Tumbabiro and Urcuqui consistently showing the highest potential regardless of the weighting scheme.

season (March-June) reduces GHI by 10%, with no necessitating seasonal energy storage or hybrid systems.

As shown in the Figure 7(b), the GHI parameter aligns with Tukey's analysis, where the parish of Urcuqui shows the highest radiation values. Additionally, the same seasonal trend is observed across data from NASA Power and Solcast, verifying the accuracy and consistency of the data.

5.2 Feasibility of PV system in San Miguel de Urcuqui

The photovoltaic potential across Urcuqui canton was systematically evaluated by integrating geospatial analysis with energy generation modeling. Using

Table 14. Comprehensive photovoltaic potential assessment by parish using equal weighting criteria.

Parish	Total Area (km^2)	Suitable Area (km^2)	Capacity (MW)	Generation (GWh/yr)	Homes Powered
Cahuasqui	126.00	1.17	11.7	19.21	4,803
Pablo Arenas	55.00	4.65	46.5	76.37	19,093
San Blas	73.93	6.28	62.8	103.14	25,785
Tumbabiro	37.61	22.85	228.5	375.21	93,803
Urcuqui	60.04	26.35	263.5	432.75	108,188
Total	**352.58**	**61.3**	**613**	**1024.22**	**251,672**

Note: Calculations based on Equal weighting criteria suitable areas shown in Figure 10. Assumes installation density of 10 MW/km^2, system efficiency of 82%, and average household consumption of 4 MWh/year based on Ecuadorian rural energy statistics [45]. Total area for La Merced de Buenos Aires not included in parish-specific calculations.

Table 15. Sensitivity analysis of scenario-based suitability.

Metric	Economic	Environmental	Balanced	Range
Estimated Suitable Area (km^2)	187.5	46.9	61.3	140.6
Percentage of Canton Area (%)	60.2	15.0	19.7	45.2 pp
Primary Suitability Class (0.8–1.0)				
% of Suitable Area	10.62%	2.66%	3.48%	–
Most Suitable Parish	Urcuqui	Tumbabiro	Urcuqui	–
% of suitable area	(45%)	(32%)	(42%)	
Spatial Characteristics				
Classification	Low	High	Medium	–
Cluster count	3	12+	6–8	
Area Change Relative to Balanced	+205.9%	–23.5%	Baseline	–
Critical Conflict Zones				
Classification	Minimal	Extensive	Moderate	–
% of Excluded Area	(5%)	(40%)	(18%)	

Note: Primary Suitability Class refers to areas with the highest suitability scores (0.8–1.0). Conflict zones represent areas where suitability criteria show direct opposition between economic and environmental priorities.

the Photovoltaic Potential Index (PVPI) defined in Equation 5, the suitable area for solar panel installation was quantified for each parish. The comparative analysis of suitable areas under different weighting criteria—Environmental, Economic, and Equal weights—is presented in Figure 10, revealing distinct spatial patterns across the canton.The equal weighting scenario was selected for photovoltaic potential assessment, as it represents a balanced approach that incorporates both environmental conservation and economic feasibility considerations. This integrated methodology identified substantial variations in solar development potential across parishes, with Urcuqui parish emerged as the most promising location, containing 26.35 km^2 of suitable area, which represents 43% of the canton's total photovoltaic potential (61.3 km^2) under the balanced weighting scenario. Following Urcuqui, Tumbabiro and San Blas parishes demonstrated significant capacity with 22.85 km^2 (37%) and 6.28 km^2 (10%) of suitable areas, respectively. These three southeastern parishes collectively account for 90% of the total suitable area identified in the canton. The pronounced concentration of optimal sites in these southeastern parishes aligns with favorable solar irradiation patterns, suitable terrain morphology, and reduced environmental constraints.

5.3 Sensitive Analysis of Scenarios

The resulting suitability maps (Figures 8 and 9) reveal significant quantitative and spatial sensitivity relating to decision-making priorities under three distinct weighting scenarios. To systematically evaluate this sensitivity, a quantitative assessment was conducted by comparing the weight sub-criteria and by examining the differences in spatial patterns observed in each scenario. The results, summarized in Table 15, demonstrate that placing different emphases on economic, environmental, and balanced criteria can alter the extent and distribution of viable solar PV deployment sites in Urcuqui.

In terms of spatial analysis, Urcuqui parish is identified as consistently optimal across all scenarios, although its dominance varies from 45% of the suitable area in the economic scenario to being surpassed by San Blas in the environmental scenario. The southeastern area (comprising Urcuqui, Tumbabiro, and San Blas) remains viable in all scenarios, demonstrating its resilience despite variations in weighting. In contrast, the parishes of Pablo Arenas and Cahuasqui show consistently low suitability (less than 10% across all scenarios), representing stable exclusion zones.

In terms of variability of criteria, GHI is the fundamental energy driver, and slope is a primary economic and engineering constraint. The model's outcome is found to be highly sensitive to the defined thresholds (e.g., the 4.5 kWh/m²/day cutoff for GHI and the 15° limit for slope) although the GHI defines the area of exclusion and suitability, the Land Use and Distance to Rivers models demonstrated moderate sensitivity, with $\pm$12.7% and $\pm$11.1% respectively. These criteria act as significant constraints than as drivers defining the most promising areas (0.8-1) for solar farms. Comparing the three different scenarios, the areas vary a 6% (Economic vs Balanced) and 2% (Environmental vs Balanced).

It has been demonstrated that minor alterations in perceived importance can result in substantial changes to the configuration of excluded zones, particularly in topographically complex regions. The finding that no single criterion, when varied within a reasonable margin of error, causes a catastrophic shift in outcomes (e.g. >50% change in area) lends further support to the robustness of the AHP-derived weight structure.The analysis confirms that, although the total area of suitable land is highly sensitive to weighting priorities, the relative parish ranking remains stable. The southeastern parishes consistently outperform the northern areas. This stability in geographic priorities, despite variations in total area, validates the robustness of the underlying spatial analysis, emphasising the critical importance of transparent, participatory weight selection in regional energy planning.

5.4 Socioeconomic Considerations and Implementation Challenges

5.4.1 Land Use Conflicts and Agricultural Impacts

The implementation of renewable energy systems in agricultural regions requires careful consideration of potential land use conflicts (Table 16). Converting fertile agricultural land into a solar park means that this land can no longer be used for growing crops or raising livestock. In a canton such as Urcuquí, where 68% of the population depends on agriculture, this poses a direct threat to local livelihoods, food security, and the region's economic base [34]. A large-scale conversion could lead to the displacement of farmers, changes in the structures of rural communities, and potentially higher land prices, making farming difficult for future generations.

Table 16. Land use analysis for suitable energy sites.

Land cover Type	Area Suitable for PV (ha)	Conflict Level
Active Agriculture	1,240	High
Pastureland	3,560	Medium
Shrubland	4,380	Low
Bare Soil	2,150	None
Urban Areas	180	Prohibited

The goal of modern energy planning is not simply to cover agricultural land with solar panels, but to find solutions that allow for coexistence and mutual benefit. This is where agrivoltaics (or Agri-PV) comes into play, consisting of integrated systems in which energy generation complements agricultural production rather than replacing it. Photovoltaic installations also indirectly contribute to mitigating the "heat island" effect and albedo change by promoting the restoration of already disturbed lands over intact ecosystems.

In Urcuqui, where 68% of the population is employed in agriculture, large-scale conversion of fertile land into solar farms poses direct risks to local livelihoods, food security, and the rural economy, the agrivoltaic (Agri-PV) model is not only feasible but recommended. Successful implementation requires a participatory approach, including:

- **Stakeholder Workshops** with local farmers and community leaders
- **Benefit Sharing Mechanisms** such as electricity discounts or revenue sharing

- **Training Programs** for local maintenance technicians
- **Adaptive Management** plans to address emerging concerns

5.4.2 *Alignment with National Energy Planning*

The projects listed in Table 17 are included in the results of this study and show 70% alignment with the areas identified in Ecuador's Electricity Master Plan. The 30% of the other areas correspond to the assessment of conflicts due to agricultural production.

Table 17. Urcuqui energy projects.

Photovoltaic Projects	State	Capacity (MW)	Estimated Investment (USD)	Source
Parque Solar Urcuquí	Operating	1.00	-	SNI.
Parque Fotovoltaico El Carmen	Planned	20.00	18-22 millions	Final Studies.
Gran Solar Urcuquí	Planeed	45.50	40-45 millions	In Evaluation.

6 Conclusion

This study developed and applied a GIS-based multi-criteria decision analysis framework to evaluate solar energy potential in San Miguel de Urcuqui canton, Ecuador. By integrating climatic, economic, and environmental criteria within an Analytic Hierarchy Process across three decision-making scenarios, the research provides spatially explicit optimal siting for photovoltaic deployment.

Urcuqui parish possesses the highest solar potential, with 26.35 km² of suitable area under the balanced scenario, representing 43% of the canton's total suitable area (61.3 km²). Tumbabiro and San Blas follow with 22.85 km² (37%) and 6.28 km² (10%), respectively. These three southeastern parishes collectively account for 90% of the total suitable area and consistently emerged as most favorable across all scenarios, confirming analytical robustness despite weighting variations.

The total suitable area of 61.3 km² translates to 613 MW of installed capacity. Applying the photovoltaic potential formula established in Eq. (6)—including an installation density of 10 MW/km², a usable area factor of 0.85, and an average peak sun hour of 4.5 h/day—the estimated annual electricity generation is 855.6 GWh. This is sufficient to power approximately 213,900 Ecuadorian households, based on the national average rural consumption of 4 MWh per household per year.

This generation potential represents a significant contribution to the energy security of Imbabura Province and supports Ecuador's national renewable energy targets. The spatial concentration of suitable areas in the southeastern parishes provides clear prioritization guidance for regional energy planning and infrastructure investment.

This research addresses a critical gap in Ecuador's renewable planning by shifting focus from large-scale projects to site-specific, decentralized solutions appropriate for Andean contexts. The framework successfully adapted global best practices to local conditions, incorporating páramo protection, seismic considerations, and agricultural integration. The identification of 1,240 ha of active agricultural land within suitable areas highlights both the challenge of land-use conflict and the potential for agrivoltaic systems. However, the feasibility of agrivoltaics in Urcuqui remains subject to constraints including high-altitude conditions, crop compatibility, and potential impacts on mechanized farming, requiring further pilot studies to assess technical and economic viability under local conditions.

The findings provide actionable information for multiple stakeholders: municipal planners can prioritize permitting and zoning in high-suitability zones; national ministries can validate and refine the areas identified in Ecuador's Electricity Master Plan, with which this study shows approximately 70% spatial agreement; and communities and investors benefit from quantified generation capacity and household equivalencies to support project feasibility assessments.

Limitations of this study include the omission of grid integration costs specific to Urcuqui's weak rural network, seasonal storage requirements due to intra-annual irradiance variability, and a lifecycle-based economic feasibility assessment incorporating local labor and material costs. Addressing these aspects in future research will strengthen the pathway from site identification to project implementation.

Future work should extend this methodology to hybrid PV–small hydropower systems, leveraging Urcuqui's abundant hydrological resources to mitigate solar intermittency. Additionally, participatory frameworks engaging local landowners and agricultural communities should be developed to ensure socially inclusive energy transitions.

This study demonstrates that rigorous multi-criteria spatial analysis can identify substantial renewable energy potential even in data-constrained environments. By delivering a replicable methodological framework and specific, actionable results for Urcuqui, this research directly contributes to Ecuador's sustainable development goals, energy sovereignty, and low-carbon energy transition.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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