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FIND THE BEST SPOTS TO PUT SOLAR POWER PLANTS USING GEOGRAPHIC INFORMATION SYSTEM (GIS) DATA

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AbstractSolar power has grown in popularity and production capability in recent years, and it is now widely regarded as a leading renewable energy source. Choosing the right spot for these plants is crucial if you want to maximise output and harvests. This study proposes a methodology that may use geographic information system (GIS) technologies to practically automatically find and evaluate the best locations to install solar photovoltaic plants. To evaluate expansive tracts of land, we suggest using a multi-criteria analysis with 10 weighted criteria that account for the energy and area needs of each installation. In order to rank the sites from best to worst, the approach uses a location coefficient that takes into account the relative importance of the selected criteria. With the use of a multi-criteria analysis and a weighing system that is also objective, based on logical criteria, and statistically consistent, the methodological approach is much more consistent than conventional alternatives, even when compared to comparable research efforts. Though applicable in different settings, this novel approach is tested in Cantabria (northern Spain).

Keywords: renewable energy; methodology; Saaty; weighting; factors; consistency; GIS

1. Introduction

Energy is one of the most important vectors for social development, economic growth, and human well-being [1]. Thus, the seventh goal of the United Nations Sustainable Development Goals seeks to "Ensure access to affordable, secure, sustainable and modern energy", one of the main targets of which is to "Increase significantly the share of renewable energy in the energy mix".

The alternative lies in the exploration of renewable sources such as solar, wind, geothermal, biomass, and hydropower. The use of solar energy is one of the most popular renewable energies at present, along with wind energy. This is due to the fact that it is a naturally abundant resource, widely available and economical [2]. Solar and wind energy supply 90% of the renewable energy generated, accounting for 60% and 30% of total renewable energy production, respectively [3].

Solar energy is defined as the production of energy from irradiation from the Sun [4]. Given that it is a resource that can be easily harnessed almost everywhere on the planet, this was the renewable energy with the greatest increase in installed production capacity worldwide in 2021 [5], making it one of the best options for meeting future energy demands in a sustainable manner [6], as a consequence of the need to reduce greenhouse gas emissions [3].

Solar energy has two possible ways of generating energy, photovoltaic solar energy, and solar thermal energy [7]:

- In the first alternative, the transformation of solar energy into electricity is carried out by photovoltaic panels, in which solar radiation excites electrons in a semiconductor device by generating a small potential difference by a photo-electrical process [8]. The electrons are able to transform and become part of a current in an electrical circuit [9].
- In the second one, energy from the Sun's rays is harnessed to generate heat in a clean and environmentally friendly way [10]. Electrical energy is produced when the heat drives a heat engine connected to a generator.

Solar photovoltaic technology has been the fastest growing renewable energy source in recent years as a result of the increased efficiency of photovoltaic cells, reduced manufacturing costs, ease of installation, and applicability in different environments [11]. According to the data, the installed capacity of solar photovoltaic energy has grown from 70 GW in 2011 to 942 GW by 2021 [12]. As a result of its simplicity of installation, low cost of service, low maintenance, reliable and silent investments, it accounts for most of the investments for the construction of large-scale photovoltaic power plants. The first photovoltaic installations were limited to 1 MW, however, as a result of the development of photovoltaic technology, it is now possible to build extremely large plants with a capacity of more than 100 MW [13].

The determination of the optimal site selection for photovoltaic plants is a fundamental process since this type of installation depends on environmental, technological, economic, and social factors that determine the economic, energetic, and constructive viability of a sustainable energy project [14]. In this type of spatial decision research, the most popular methodology for the determination of optimal site selection for photovoltaic plants is based on the combination of Multi-Criteria Decision Analysis (MCDA) or Multi-Criteria Analysis (MCA) and Geographic Information System (GIS) with the objective of evaluating the most suitable locations [15]. In general terms, the method is based on the determination of meteorological, climatic, topographical, economic, or social criteria [16], determining aspects that affect the solar resources and the condition of the terrain to house a photovoltaic installation, and then carrying out a multi-criteria analysis with geospatial information [17]. Multi-Criteria Analysis allows the assignment of weights to the criteria in order to analyze the relevance of some criteria over others by means of different methodologies such as Analytic Hierarchy Process (AHP), Network Analysis Process (NAP), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to compare and evaluate the different site selection alternatives [18]. The criteria selected and the number of them are very variable from one research to another [15,19]. The energy criteria are those that refer to the energy production or photovoltaic power generation potential (PVOUT), which depends on environmental factors such as radiation, temperature, luminosity, humidity, or cloudiness, factors that vary rapidly, changing and conditioning the production of the photovoltaic panels [20]. Previous investigations consider these criteria by evaluating their average value over time, such as annual average temperature or humidity [21,22]. In contrast to the general conception, the present research proposes a typification of these criteria based on the measurement of the variables at three key points along the day to establish a representative average value that allows the selection of the optimal location. Similarly, this work proposes a methodology for the quantification of relevant qualitative criteria so that these can be taken into account in the multi-criteria analysis.

This research designs the procedure for carrying out a multi-criteria analysis, which allows the optimal location of photovoltaic solar plants to be sought while optimizing their energy production. The final result is a map in which the territory is classified according to its suitability for the implementation of this type of installation. At present, there are other studies with the same objective, which justifies the interest of this type of research, although the main difference is that this research focuses on the choice and quantitative treatment of the chosen criteria, as well as the weighting of these criteria in an objective, logical, and statistically consistent manner.

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2. Classical Methodological Approach

The production of solar photovoltaic energy depends mainly on the solar radiation available on the Earth's surface [23], which does not affect all regions of the world equally. Latitude is the main factor that determines the solar photovoltaic potential of a territory [24].

Based on this information, there are maps of photovoltaic potential in terms of the kWh that could be generated per m^2 [25]. These maps usually classify the Earth's surface into zones where solar photovoltaic energy production can be most efficient.

The most relevant issue is that considering solar radiation as the most relevant factor, circumstances can change this situation:

- Insufficient land area to make a significant difference in solar radiation.
- Accumulation of factors that can modify solar radiation conditions independently (relief, orientation, etc.).
- Criteria that, while affecting the performance of the installation, are not directly related to solar radiation (temperature, cloud cover, etc.).

Using this single criterion would lead to overly simplistic results. One of the main factors influencing energy production is climate. Nowadays, data are available to simulate multiple criteria to model the behavior of an installation in a way that is very close to reality, making it possible to find the optimum location, achieve high efficiency in generation, and optimize the use of the resource [26].

This research is justified on the basis of the current need for a procedure that allows a multi-criteria analysis applicable to large areas of territory, determining the optimal location of a solar photovoltaic plant. This research varies substantially from traditional procedures based on subjective weightings to determine the best location. This methodology proposes a novel combination and weighting, using a statistical procedure to evaluate the consistency of the weighting.

When performing a multi-criteria analysis for the optimal location of solar photovoltaic plants, one of the main problems is to consider various environmental, social, and technological criteria simultaneously, in order to decide where to install the photovoltaic panels. Geographic Information Systems (GIS) allow geospatial multi-criteria analyses to be carried out almost automatically over large areas of territory, by making decisions in a logical, objective, and rational manner [27,28], helping to determine the optimal location of solar plants, geothermal farms, wind farms [29], or the solution of conflicts in territorial planning processes [30].

2.1. Classification of Classical Criteria

Currently, there are several studies that apply multi-criteria analysis for the selection of the best location for solar photovoltaic plants [31–34]. The difference between all of them is the choice of criteria to be considered to determine the optimal location. However, certain criteria are decisive and common to most of the existing research in this field [35]. Most scientific research classifies the criteria into the following three main groups.

2.1.1. Energy Criteria

The energy criteria make it possible to determine the most suitable geographical areas solely on the basis of the amount of energy that the photovoltaic solar panels are capable of generating. There may be other socio-economic or environmental reasons, but if the solar plant is not energetically viable, the project will not be interesting. The most commonly considered energy criteria are:

- Solar radiation. Defined as the amount of solar energy received by a point on the Earth's surface (kWh/m^2), it is one of the most important factors in determining solar energy potential. Since the intensity of solar radiation depends on its inclination on the Earth's surface, it depends mainly on latitude. Several authors use this criterion to establish the optimal location for such installations [30,31,33,36]. However, it may be of little significance in small territorial analyses, with small latitude variations [37].

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- The temperature in the study area can be a key criterion for analyzing the optimal location [38]. Some authors consider areas with average temperatures between 10 and 20 °C to be suitable in terms of energy production [33]. The difficulty lies in choosing the representative temperature or parameter to use to assess this criterion [39].
- The hours of sunshine per day are a decisive factor: the more hours of sunshine, the more energy production. Possibly for this reason, many authors consider this criterion to be one of the most important ones [33,40]. However, it presents the same problem as solar radiation for small areas of territory, as it depends mainly on latitude.
- Orientation. This criterion determines the incidence of solar radiation, depending on the shaded areas due to the orientation of the terrain and its influence on generation [41]. South or southeast orientations are best suited to maximize electricity production [33,40].
- Humidity. This criterion conditions energy production: solar radiation is absorbed by humidity, decreasing the incident radiation on the solar panel [34], and therefore energy production. Different authors qualify this criterion as fundamental in multi-criteria analysis [34,36], generally considering the number of rainy or cloudy days.

2.1.2. Geographical Criteria

This set of criteria aims to take into account a series of infrastructures that, although they do not allow for an improvement in energy production, facilitate the investment necessary to start up this type of installation. Among the criteria most commonly used in previous research, the following can be considered:

- The slope of the terrain. This is one of the criteria that can have the greatest influence on the location of any installation of this type. An increase in the slope of the land can make the construction and installation of the photovoltaic plant unfeasible, as it increases the costs of construction and transport of materials. Various studies [32,34] include this criterion to be taken into account in multi-criteria analyses [42].
- Grid connection. This is a necessary infrastructure that must be considered when analyzing the distance between the territory under analysis and the nearest electricity grid for a good location for the installation [43].
- Accessibility. Proximity to transport/communication routes is essential to guarantee the viability of the photovoltaic plant [44], as they are necessary for the construction of the installation and subsequent access for operators [45]. This is one of the main geographical criteria and the most repeated in research of this type [31,33].
- Classification and use of the land. The urban classification in the land use plan may make the location suitable if it is indicated for its use, or restrictive if it is on specially protected rural land [46,47].
- Proximity to population settlements. This criterion has two aspects, given that the proximity of the plant to energy-demanding population centers reduces energy transport costs and energy dissipation, but the territorial organization restricts the location of generation plants within urban centers or cities [36].

2.1.3. Environmental Criteria

The third type of criteria used by most authors are environmental ones of a restrictive nature, considering areas that due to their features preclude the development of a project of this type [48]. There are certain areas of the territory that, given their high ecological value and vulnerability to certain external agents, are protected, preventing any activity from being carried out there [49]. These areas include the following:

- Special Protection Areas;
- Natura 2000 Network;
- Areas of cultural and scenic interest;
- National and Natural Parks;
- River banks.

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There may be many other criteria to be taken into account in an analysis for the optimal location of a solar photovoltaic plant, but the ones listed here are the ones currently used by different researchers in similar works and can be considered the most significant.

2.2. Weighting of Classical Criteria

Selecting the criteria whose analysis is most convenient to find the optimal location is the first step to carrying out a correct study using GIS. However, developing a multi-criteria analysis involves weighting the criteria appropriately, which is equally or more important than the selection of criteria itself [35].

In these cases, it is common to employ certain methods for weighting based on the use of weighted averages with generally random assignment of weights [50]. Examples of these methodologies are the Analytic Hierarchy Process, Network Analysis Process, Technique for Order of Preference by Similarity to Ideal Solution [18], Direct Ranking Method [51], Weighted Linear Combination [52], Linear Interpolation [53] or Inverse Variance Method [54]. There are also other methods that have fallen into disuse because they are considered less accurate, subjective, and unproven, such as the Multi-Attribute Utility Method (MAUT) [55] or the Outranking Approach Method [56].

3. Materials and Methods

3.1. Choice and Classification of Criteria

In this first phase of the methodological proposal, the criteria chosen on the basis of the research carried out are collected. A total of 10 criteria are classified by levels, assigning each of these levels an internal score according to their suitability for the installation of a photovoltaic plant.

3.1.1. Temperature

Temperature is directly related to the performance of the panel, and therefore to energy production [31,33]. The ideal operating temperature for photovoltaic panels is between 20 and 25 °C, with maximum efficiency at 25 °C. At higher temperatures, the efficiency can be reduced as a result of voltage drop in the panels due to heating of the semiconductor. At higher temperatures, efficiency can be reduced as a result of voltage drop across the panels due to heating of the semiconductor (silicon) [57]. It is estimated that for every degree (°C) above the ideal 25 °C, the power generated decreases by 0.35% [58]. However, low temperatures do not penalize production as long as radiation levels are adequate [59].

In addition to defining suitable temperature ranges, in order to take temperature as a criterion for the analysis of the location of a solar photovoltaic plant, it is important to select which temperatures are to be taken into account for the analysis. Photovoltaic panels only produce energy when there is sunlight, and only daytime temperatures are relevant.

Although nowadays automatic weather stations are capable of taking continuous data, during the day there are three very representative moments to measure the ambient temperature, collecting the variations that occur.

- The first one is at 7:00, Universal Coordinated Time (UTC), when the temperature is assumed to be at lower levels because it is the first hours of daylight.
- The second, at 13:00, allows us to expect the highest temperatures because the Sun is close to its highest position, i.e., at the zenith.
- The last one is at 18:00. In winter, it is the time of the last rays of sunshine, and during the summer at this time, the temperature has already dropped.

Given the variety of temperature data and the difficulty of choosing the most representative indicator, the research proposes to establish as temperature indicator a representative value that is obtained as the sum of partial sub-indicators that depend on the monthly average temperatures at 7.00, 13.00, and 18.00.

This sub-indicator depends on this average temperature and has to take the values set out in Table 1 depending on its suitability for photovoltaic generation.

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Table 1. Assignment of the thermal indicator by ranges of the mean temperatures.

Temperature (°C)	Sub-Indicator
0 < Value ≤ 5	1
5 < Value ≤ 10	2
10 < Value ≤ 15	3
15 < Value ≤ 20	4
20 < Value ≤ 25	5
25 < Value ≤ 30	4
30 < Value ≤ 35	3
Value > 35	2

These temperature ranges can be organized between the maximum and minimum values of the temperatures of the area under analysis and the classes into which the total range is to be subdivided. In addition, the value of the point indicator to be obtained for each weather station should be the sum of the 36 corresponding values of the indicators for the 12 months of the year at the proposed 3 daily hours.

3.1.2. Orientation

Orientation is one of the energy criteria that most influences energy production [60]. This is why it is one of the criteria selected in this proposal, as well as in other research [30,32,33,36]. It is known that south-facing panels rather than north-facing ones increase electricity generation. In addition, it is known that areas facing west have better generation performance than east-facing areas. Thus, it is possible to establish the criteria classification as shown in Table 2.

Table 2. Classification for the assessment of the criterion of the orientation of the terrain according to its angle to the north.

	Orientation	Score
North	0° < Value ≤ 45°	0
Northeast	45° < Value ≤ 90°	1
Southeast	90° < Value ≤ 135°	3
South	135° < Value ≤ 225°	5
Southwest	225° < Value ≤ 270°	4
Northwest	270° < Value ≤ 315°	2
North	315° < Value ≤ 360°	0

3.1.3. Humidity

Humidity is defined as the amount of water vapor present in the air. Along with carbon dioxide, it is the most important absorber of solar energy in the atmosphere [36]. High humidity absorbs shortwave solar radiation, reducing the total amount of irradiance that can be used by the panel for electricity production [61]. Humidity values below 30% are suitable for solar photovoltaic generation, which implies scoring these areas with a higher score [36].

Therefore, it is proposed to establish the same methodology followed for temperature, obtaining a representative humidity value as the sum of a series of monthly average values of relative humidity at 7.00, 13.00, and 18.00 solar hours. The different humidity ranges are then assigned a score, as shown in Table 3.

Table 3. Classification of the suitability of the location according to the percentage values of the humidity ranges.

Relative Humidity Ranges (%)	Score
90 < Value ≤ 100	0
80 < Value ≤ 90	1
70 < Value ≤ 80	2
60 < Value ≤ 70	3
50 < Value ≤ 60	4
Value ≤ 50	5

3.1.4. Cloud Cover

The consideration of this criterion is one of the main contributions of this work with respect to previous research. Cloud cover directly affects the energy generated by the solar panels, as the production is not the same on sunny days as it is on days when the sky is overcast or rainy. During cloudy days, although clouds affect the radiation, the modules work at 10–15% of their performance producing energy.

In order to implement this criterion, meteorological data reflecting the cloudiness of the study area are needed. The most straightforward option is to obtain the annual sunny days measured by each of the weather stations considered in the analysis: with the whole series of meteorological data the average sunny days have to be calculated and five ranges have to be established.

Following the same procedure used for humidity and temperature, the weather value will be taken during all months of the year at the same times: 7:00, 13:00, and 18:00. Depending on the suitability of the cloudiness, values will be attributed to obtain the cloudiness indicator (Table 4).

Table 4. Cloud cover indicator for electricity generation with photovoltaic panels as a function of cloudiness range.

Cloudiness Ranges (%)	Sub-Indicator
0 < Value ≤ 2	5
2 < Value ≤ 4	4
4 < Value ≤ 6	3
6 < Value ≤ 7	2
7 < Value ≤ 8	1

3.1.5. Latitude

Another energy criterion that is very important in the analysis of the optimal location of a photovoltaic solar plant is latitude (ϕ): the angle formed by the vertical of a point with the equatorial plane, which is measured from the Equator towards the north as positive and negative towards the south. Latitude determines the inclination at which the Sun's rays strike the Earth's surface, directly affecting the generation of photovoltaic panels. Areas closer to the Equator, with lower latitudes, receive more solar energy. Latitude is directly related to two parameters, irradiance (a quantity describing the radiation or intensity of solar illumination reaching the Earth's surface measured as an instantaneous power per unit area, in kW/m^2 per day) and insolation (the total amount of solar energy received at a given location during a specified time period, often in units of kWh/m^2 per day) [31,36]. The number of sunshine hours per day is taken into account in the cloudiness criterion as well, where the annual sunshine days are established.

Both parameters depend on latitude, a geographical criterion that can be introduced into the multi-criteria GIS analysis in a relatively simple way. In order to implement this criterion, it will be necessary to create a map where five ranges in the form of strips within the study area are represented by lines of constant latitude and given a score according to their suitability: increasing latitude will reduce the score.

3.1.6. Terrain Slope

The classification of the slope of the terrain is fundamental, especially in areas with steep terrain. Most authors consider that above 25% it is unfeasible to carry out any project of these characteristics, with flat areas favoring both installation and access for subsequent maintenance [62]. It is proposed to classify the slope of the terrain according to the values of the indicator in Table 5.

Table 5. Assessment of the index as a function of the slope intervals of the terrain.

Terrain Slope Ranges (%)	Score
Value > 25	0
10 < value ≤ 25	1
5 < value ≤ 10	3
0 < Value ≤ 5	5

3.1.7. Connection to the Electricity Grid

The optimal location includes the existence of power lines that allow the energy generated to be transported to the consumption or transformation points, so that the shorter the distance, the higher the score, and vice versa [63]. Taking into account the large number of power lines that may be present in the electricity system at different voltages, those with a voltage equal to or greater than 60 kV will be analyzed. Table 6 shows the values of the indicator.

Table 6. Grid connection criterion classification and scoring depending on the distance of the location to existing power lines.

Distance to the Power Line (m)	Score
Value > 2000	1
1000 < Value ≤ 2000	2
500 < Value ≤ 1000	3
250 < Value ≤ 500	4
0 < Value ≤ 250	5

3.1.8. Accessibility

If there are no roads close to the plant that allow access to it, it will be necessary to build them, increasing the initial investment of the project. The existence of nearby roads increases the viability of the project [31,37]. For the analysis, asphalted roads that allow adequate access are taken into account. The proposed score establishes five ranges according to distance (Table 7).

Table 7. Score of the existing distance to communication routes according to ranges.

Distance to the Communication Road (m)	Score
Value > 2000	1
1000 < Value ≤ 2000	2
500 < Value ≤ 1000	3
250 < Value ≤ 500	4
0 < Value ≤ 250	5

3.1.9. Land Classification

This criterion reflects the legal restrictions on the use that can be made of the territory itself, with three main types of land: urban, developable, and undevelopable land, which is also known as rustic [30]. According to the legislation, the construction of this type of project can only be carried out on land classified as urban, restricting the uses of the different types of land. Urban and undevelopable lands are assessed with a score of 0 (Table 8) and are excluded from the analysis.

Table 8. Land type classification and scoring and scoring for optimal site exclusion and selection.

Urban Typology	Score
Urban land	0
Non-urban land	1

3.1.10. Environmental Protection Areas

The environmental criterion involves the restriction of legally protected areas, in which it is not possible to carry out the project [30,31,33,64]. Within these protection areas, all zones established according to the national or regional regulatory framework are considered, excluding all protected areas from the analysis (Table 9).

Table 9. Classification of the environmentally protected areas for their exclusion from the optimal location of energy projects.

Environmental Area	Score
Special Protection Area	0
Natura 2000 Network	0
Area of scenic and cultural interest	0
National and Natural Park	0
River banks	0
Other zones	1

3.2. Weighting of Selected Criteria

The weighting method proposed in this research is known as "Analytic Hierarchy Process" (AHP), allowing the criteria to be ranked and establishing the relative degree of priority between them [65], based on a matrix of compared pairs and their normalized matrix from the Fundamental Scale [66] (Table 10). Thus, each criterion is given its own weight to model the optimal photovoltaic plant location, eliminating subjectivity [67]. This method is particularly suitable for decision-making when there is little information, or if the decision has to be made on the basis of qualitative criteria [60].

Table 10. Fundamental Pairwise Comparison Scale [60] for the definition of the weighting of the selected criteria.

Scale	Definition	Explanation
1	Equally important	Both criteria contribute equally to the objective
3	Moderate importance	Experience and judgment somewhat favor one criterion over the other
5	High importance	Experience and judgment strongly favor one criterion over the other
7	Very high importance	One criterion is very strongly favored over the other. In practice, its dominance can be demonstrated
9	Extreme importance	The evidence strongly favors one factor over the other
2, 4, 6 and 8	Intermediate values between the above when it is necessary to qualify	

To obtain the weighting matrix, first of all, a matrix of compared pairs is created where all the criteria are set against each other, ranking them on the basis of Saaty's Fundamental Scale (Table 10). The matrix is then normalized to obtain the average vector of sums or global priorities, which allows the average of the elements of the column matrix (λ_{max}) to be calculated. Taking into account the number of components applied in the matrix (n), the inconsistency coefficient (IC) is calculated.

$$IC = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (1)$$

Finally, the obtained inconsistency coefficient is compared with the random consistency values (RCV, Table 11).

Table 11. Random consistency values as a function of the matrix rank for the selected criteria.

n	3	4	5	6	7	8	9	10	11	12
RCV	0.525	0.882	1.115	1.252	1.341	1.404	1.452	1.484	1.513	1.535

The random consistency is chosen according to the number of components of the matrix, in order to subsequently calculate the consistency ratio (CR) as the quotient between the calculated IC and the random consistency.

$$CR = \frac{IC}{RCV} \quad (2)$$

Consistency is considered to exist when the consistency ratio does not exceed the percentages shown in Table 12. If it is met, the matrix is consistent, and the criteria can be weighted. If not, the matrix of compared pairs should be reevaluated.

Table 12. Consistency ratio values as a function of matrix size for the selected criteria.

Matrix Size	Consistency Ratio (CR)
3	≤5%
4	≤9%
5	≤10%

Once the assignment of weights has been established, it is possible to enter the information in the GIS tool and proceed to perform the multi-criteria analysis.

4. Results

4.1. Introduction

The new methodological proposal that includes the procedures for choosing and weighting the criteria that allow the optimal location of a solar photovoltaic plant can be extrapolated and therefore applied to any country, territory, or area of interest anywhere in the world. In order to validate the methodology, in the present work it is applied to Cantabria (north of Spain, Figure 1). Spain is one of the countries with the largest solar resource in the world [68]. Spain is also at the forefront of photovoltaic patents in Europe. Due to its geographical location, Cantabria does not have the most privileged location in terms of solar radiation and hours of sunshine. However, its extension and an administrative unit favor obtaining the necessary information to carry out the multi-criteria analysis.

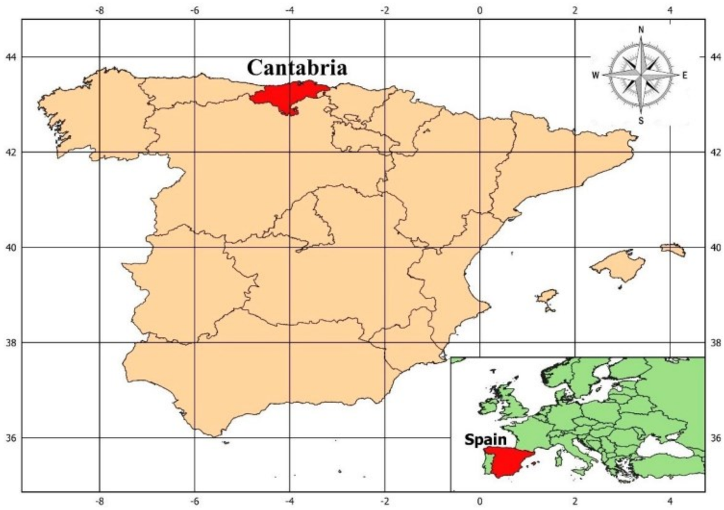


Figure 1. Location of Cantabria in the national and European contexts.

4.2. Characterization of Criteria

Before starting an analysis of this type, it is advisable to define the information available for the territory, in order to establish the criteria according to what information can be collected from each of them. The next issue requires detailing and classifying by ranges all the criteria raised in the analysis. In this case, it is proposed to score the most suitable areas with a value of 5, while the least favorable areas for installation will be rated 1. Exclusion criteria, such as urban land classification or protected areas, will be scored as 0. For the rest of the criteria, a score of 0 will mean that these territories are not suitable for installation based on that particular criterion, but they are taken into account in the analysis (Table 13).

Table 13. Evaluation of the criteria in terms of their suitability, and their color-coded representation.

Suitability	Color Code	Score
Null or excluded	Violet	0
Very low	Blue	1
Low	Green	2
Medium	Yellow	3
High	Orange	4
Very high	Red	5

4.2.1. Energy Criteria

Temperature, orientation, humidity, cloudiness, and latitude have been considered as energy criteria for this analysis.

The temperature data for Cantabria adopted were based on the records of the 18 weather stations of the State Meteorological Agency (AEMET), which are evenly distributed in the region.

For each weather station, 36 average temperature data are obtained, corresponding to the 3 h analyzed for the 12 months. From these values, the thermal indicator is assigned based on the suitability of the temperature for energy production according to Table 1. The indicator is the sum of the 36 values for each weather station.

For the case of Cantabria, ranges have been established according to the scores obtained by the stations, ranging from 101 to 132, generating five intervals (Table 14).

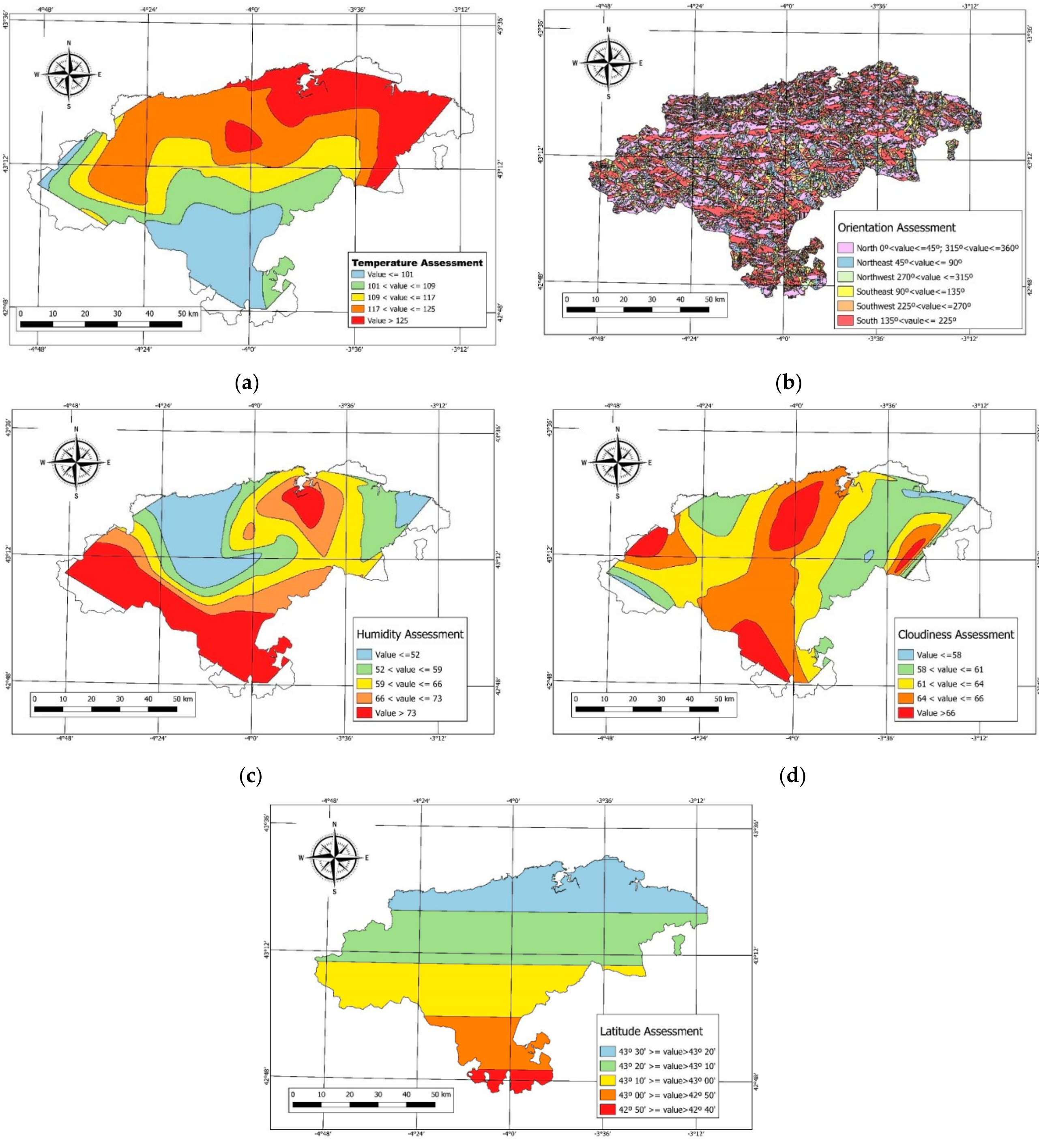
Table 14. Ranking of weather station indicator ranges based on their scores.

Indicator Ranges	Score
Value $\leq$ 101	1
101 < Value $\leq$ 109	2
109 < Value $\leq$ 117	3
117 < Value $\leq$ 125	4
Value > 125	5

Once the total thermal indicator for each station has been obtained, a representative map of the suitability of the temperature for the installation of a solar plant is generated (Figure 2a).

To analyze the orientation in GIS it is necessary to have the digital terrain model (DTM) from which the software [Qgis v.3.36.1] is able to determine the orientation of each pixel or cell of the raster file and generate a map with the classification proposed in Table 2. In this case, the DTM of the National Plan of Aerial Orthophotography of Spain of 2010 is used, with a 25 m resolution. The result obtained is shown in Figure 2b.

Like temperature, humidity is a criterion that is difficult to quantify due to the variability it undergoes in small periods of time. Based on the data from the weather stations, the average humidity values for the three selected solar hours are determined, and then their suitability is scored according to Table 3. Humidity is classified based on the scores, which in this case range from 52 to 73 so it is possible to classify the stations by ranges (Table 15).



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 2. Maps derived from the classification of the territory based on individual energetic criteria: (**a**) temperature; (**b**) orientation; (**c**) humidity; (**d**) cloudiness; and (**e**) latitude.

The score obtained from each of the meteorological stations is used to generate the representative map for this criterion (Figure 2c).

Considering cloudiness, the data provided by the AEMET allow determining for each weather station the proportion in eighths of overcast sky in each observation. If the sky is completely overcast, a cloudiness value of 8/8 is assigned (the least suitable). In the case of completely clear skies, they take the value 0/8. Given the variability of the cloudiness in a short period of time, it is subjected to the same procedure previously

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applied. Values between 0 (the most suitable) and 8 (the least adequate) are adopted, as shown in Table 4. Based on these ratings and the average monthly cloudiness values, a score has been obtained for each weather station (Table 16).

Table 15. Score classification by ranges of the humidity percentage applied to the case study of Cantabria.

Indicator Ranges	Score
Value ≤ 52	1
52 < Value ≤ 59	2
59 < Value ≤ 66	3
66 < Value ≤ 73	4
Value > 73	5

Table 16. Classification of cloudiness in ranges based on calculated scores calculated for the meteorological stations in Cantabria.

Indicator Ranges	Scores
Value ≤ 58	1
58 < Value ≤ 61	2
61 < Value ≤ 64	3
64 < Value ≤ 66	4
Value > 66	5

The ranges obtained for the cloudiness of the meteorological stations allow for representing the suitability (Figure 2d).

In Cantabria, the northernmost point of the region, with the highest latitude ($\phi = 43°30'49''$ N), corresponds to the area where the radiation is more inclined and therefore allows less generation. On the opposite side is the south of the region ($\phi = 42°45'35''$ N), to which a more direct solar radiation is attributed, being the most favorable case for generation. Between these two latitudes, the ranges shown in Table 17 are established.

Table 17. Classification of the latitude ranges of Cantabria to determine the suitability according to the solar radiation.

Latitude (φ) Ranges	Scores
$43°30' \geq$ value > $43°20'$	1
$43°20' \geq$ value > $43°10'$	2
$43°10' \geq$ value > $43°00'$	3
$43°00' \geq$ value > $42°50'$	4
$42°50' \geq$ value > $42°40'$	5

Based on these ranges, a map representing each scoring zone is generated (Figure 2e).

4.2.2. Geographical Criteria

The application of the proposed methodology to the geographical criteria (terrain slope, connection to the power grid, accessibility by communication routes, and land classification) is detailed below.

The slope of the terrain is analyzed from the DTM, through the analysis of each cell or pixel of the model using the values defined in Table 5. Based on this criterion, a map is obtained (Figure 3a) in which it can be seen that the areas closest to the coast are valued with the best score, as they have lower slopes.

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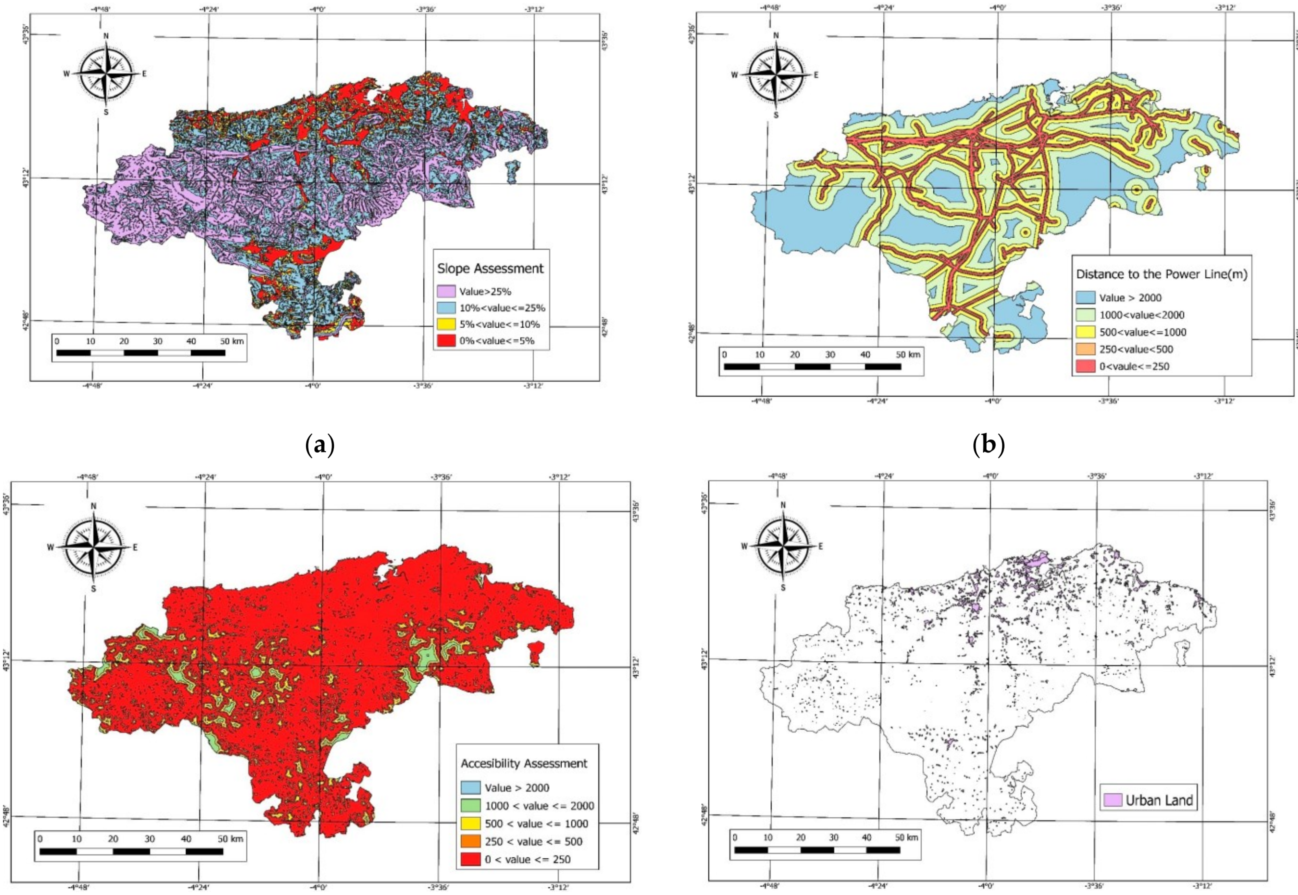

(a) (b) (c) (d)

Figure 3. Maps derived from the classification of the territory based on individual geographic criteria: (**a**) slope; (**b**) distance to power grids; (**c**) distance to communication routes; and (**d**) land classification.

Analyzing the available cartographic information of power lines over 60 kV in Cantabria, bands defined by distance to them are established according to Table 6, allowing us to obtain a map of the suitability of the territory based on the connection to the power grid (Figure 3b).

Based on the ranges of distance to communication routes (Table 7), a representative map of this criterion is generated (Figure 3c).

In Cantabria, the land used for this type of plant must be undevelopable. Although within this category there are other subcategories with restrictions, the fact is that the current cartographic information does not differentiate between these subcategories. This justifies the classification into two types of land: urban land as an exclusion zone and non-urban land as a non-exclusion zone (Table 8), as shown in Figure 3d.

4.2.3. Environmental Criteria

Cantabria is a region with incredible natural spaces whose conservation has been achieved through different figures of environmental protection. Protected areas have to be excluded from the analysis. Figure 4 represents those areas corresponding to protected zones and the zones in which it is possible to install photovoltaic panels according to this criterion.

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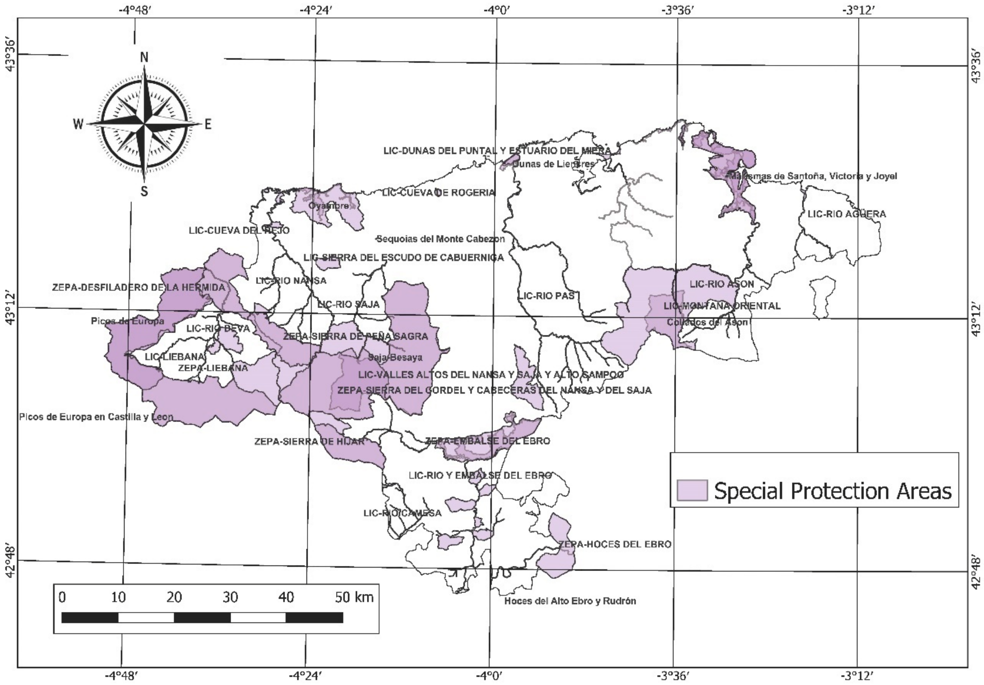

Figure 4. Environmentally protected areas, and therefore excluded from analysis. Protected Natural Spaces are represented in the darkest tone. The Special Bird Protection Areas are shown in an intermediate tone, and the Sites of Community Interest in the lightest shade.

4.3. Application of the Weighting Method

After evaluating the proposed criteria, and in order to carry out the multi-criteria analysis, they have to be weighted through the creation of the pairwise comparison matrix using Saaty's Fundamental Scale (Table 10), which compares the 10 criteria against each other, scoring them from one to nine (Table 18).

Table 18. Pairwise comparison matrix of all selected criteria for the case study of Cantabria.

		A	B	C	D	E	F	G	H	I	J
Temperature	A	1.00	2.00	3.00	3.00	5.00	5.00	7.00	7.00	7.00	2.00
Latitude	B	0.50	1.00	2.00	2.00	4.00	4.00	6.00	6.00	6.00	1.00
Orientation	C	0.33	0.50	1.00	1.00	3.00	3.00	5.00	5.00	5.00	0.50
Cloudiness	D	0.33	0.50	1.00	1.00	3.00	3.00	5.00	5.00	5.00	0.50
Humidity	E	0.20	0.25	0.33	0.33	1.00	2.00	3.00	3.00	3.00	0.25
Land classification	F	0.20	0.25	0.33	0.33	0.50	1.00	3.00	3.00	3.00	0.25
Connection to power grid	G	0.14	0.17	0.20	0.20	0.33	0.33	1.00	1.00	2.00	0.17
Accessibility	H	0.14	0.17	0.20	0.20	0.33	0.33	1.00	1.00	2.00	0.17
Terrain slope	I	0.14	0.17	0.20	0.20	0.33	0.33	0.50	0.50	1.00	0.17
Special Protection Areas	J	0.50	1.00	2.00	2.00	4.00	4.00	6.00	6.00	6.00	1.00

Once the matrix of compared pairs has been compiled, it is normalized to obtain the global priorities, the total row vector, and the column matrix between the global priorities and the row vector.

It is possible to improve the result by several iterations of the process until there are no significant variations in the priorities. Five iterations have been carried out until the results without variability have been achieved (Table 19).

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Table 19. Final weights attributed to each of the selected criteria.

		Global Priorities	Total Row Vector	Column Matrix	Final Weight (%)
Temperature	A	0.2554	2.6485	10.3687	25.54
Latitude	B	0.1713	1.7762	10.3687	17.13
Orientation	C	0.1119	1.1604	10.3687	11.19
Cloudiness	D	0.1119	1.1604	10.3687	11.19
Humidity	E	0.0563	0.5841	10.3687	5.63
Land classification	F	0.0489	0.5071	10.3687	4.89
Connection to power grid	G	0.0258	0.2676	10.3687	2.58
Accessibility	H	0.0258	0.2676	10.3687	2.58
Terrain slope	I	0.0213	0.2205	10.3687	2.13
Special Protection Zones	J	0.1713	1.7762	10.3687	17.13

The results of the CR calculation are shown in Table 20. Based on the results, it can be stated that the matrix is consistent, which allows the implementation of these proposed weights in the multi-criteria analysis.

Table 20. Consistency analysis of the normalized matrix after the fifth iteration.

Parameter	Value
λmax	10.3687
IC	0.0409
RCV	1.484
CR	2.76

4.4. Results of Optimal Placement

Once the maps for each criterion have been generated and the weights calculated, the last step of the analysis is the generation of a final map overlaying all the previous maps, with their relative weights. This map will identify the most suitable areas for location (Figure 5).

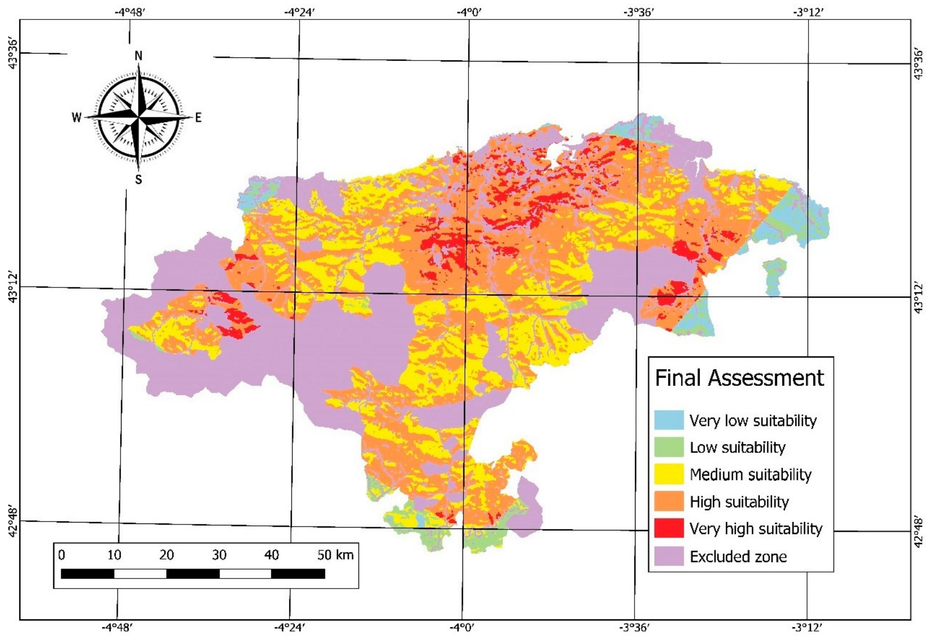

Figure 5. Final map of results after weighting.

Once the exclusion zones have been eliminated, the areas shown in Figure 6 have been obtained, with scores between 3.62 and 0.37. The areas with the highest scores (2.97–3.62)

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are the most suitable ones for the installation of a solar photovoltaic plant following the ten considered criteria.

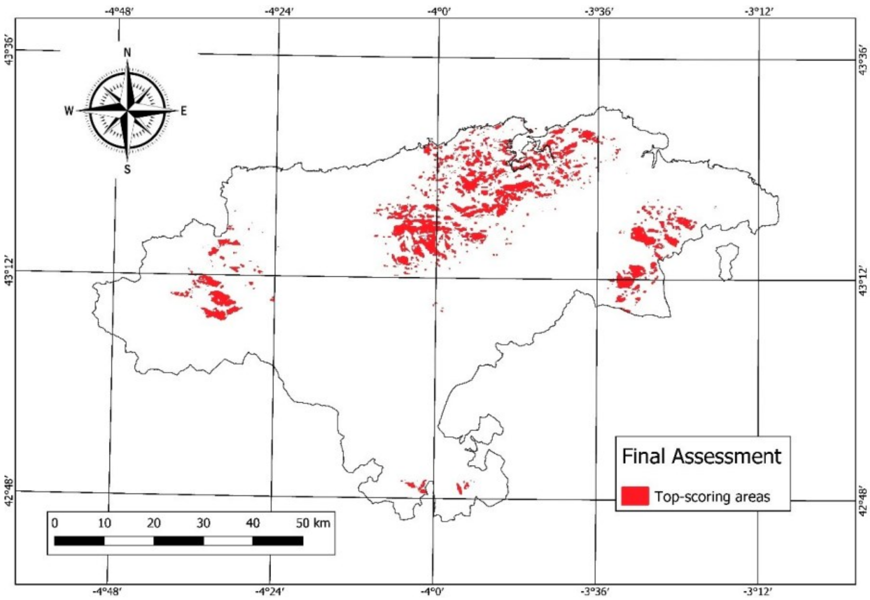

Figure 6. Areas with the highest score range.

There are 6797 differentiated suitable areas. In order to establish a more restrictive classification, they are ordered by their surface area, since in order to obtain a certain yield from a photovoltaic solar plant it is necessary to install a minimum number of panels [69]. Specifically, the ten locations with the largest extension are located very close to each other, near the municipality of Los Corrales de Buelna, in towns such as San Felices and San Mateo, or the village of La Montaña (municipality of Torrelavega). All these places are in the center of the region, as shown in Figure 7.

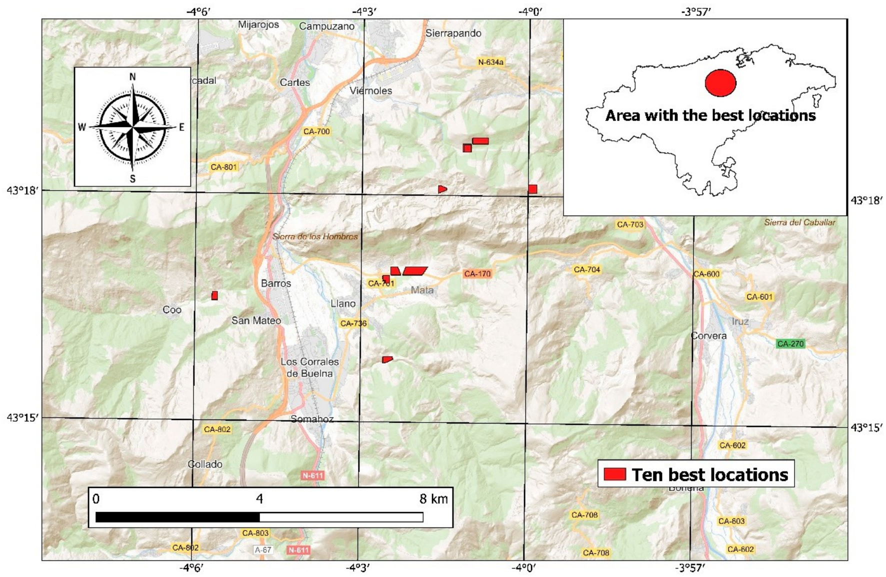

Figure 7. Optimal locations with the largest extension.

5. Discussion

Like all research, its own development involves the achievement of a series of milestones, some fully developed and others partially. This implies a series of strengths and weaknesses of the research itself. In this sense, the main strengths of the research are as follows:

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- One of the main weaknesses of the methodology is the difficulty of having a good cartographic base. The DTM that allows obtaining the orientation and slope map is fundamental, as well as the map of roads, power lines, protected areas, etc.
- Another weakness is the difficulty in obtaining information related to climate. In general, there are few meteorological stations; in the case of Cantabria (5300 Km^2), there are 18 automated meteorological stations. Not all of them collect the type of data required in this research, especially cloudiness, and the historical data in this type of station are very small compared to the 30-year series recommended for the use of meteorological data.
- The lack of coincidence of the administrative boundary of the region and the perimeter of the enclosure of the points corresponding to the locations of the meteorological stations used in the climate modeling produces interferences in the results in these areas. In order to correct them, other meteorological stations of bordering regions should be taken. In the case of Cantabria, there are 18 weather stations that do not coincide in the perimeter of Cantabria and three bordering regions with their respective meteorological centers, so it was decided to work only with the weather stations of Cantabria, being aware that there are such interferences at the edges of the map.
- The results obtained by applying the proposed criteria are based on their treatment by applying the AHP method, which is the most common and widely used method [15,18]. However, the result may vary when using other methods such as those previously mentioned, such as the Network Analysis Process, Technique for Order of Preference by Similarity to Ideal Solution, Inverse Variance Method or Outranking Approach Method.
- The methodology proposed to typify the criteria referring to energy, climate, or environmental parameters dependent on the time variable, such as radiation, temperature, cloudiness, humidity, etc., can be extrapolated to other site selection studies for other renewable energies such as wind power. However, modifications must be made. The proposal is oriented towards weighting and valuing these factors during daylight hours, which are those in which it is possible to take advantage of solar radiation. If other sources of energy were considered, e.g., wind energy, the selection of the timeframe should consider those hours in which optimal wind conditions are more likely to exist.
- The selection of criteria is one of the fundamental phases of this research. However, when considering previous works from other authors, many discrepancies can be observed from one proposal to another, and there is no consensus regarding the minimum or maximum number of criteria to be used. Software development makes it possible to implement a greater number of criteria and therefore to carry out a more complete analysis. Nevertheless, the weight of all the criteria evaluated and their incidence must be taken into account, in order to avoid evaluating criteria that are not quite relevant. In the same way, other criteria that have not been considered in this proposal and are outside of the performance of the installation, such as social acceptance or economic costs, could be included.
- The proposed methodology is based on the analysis of the optimal location of photovoltaic power plants based mainly on energy, geographic, and environmental criteria. These criteria focus to a large extent on the performance and energy production of the installation, by addressing issues related to energy efficiency and current regulations with the aim of establishing the most sustainable plant possible. However, it is also possible to consider other aspects discussed in the Life Cycle Analysis (LCA), such as social, environmental, or landscape impact, as well as the final phase of decommissioning and environmental rehabilitation. The inclusion of potential new criteria may allow a richer analysis, requiring modifications in the classical assignment of weights to the criteria by means of the Analytic Hierarchy Process.

The application to a territory of reduced extension such as Cantabria has favored the rigor of the study by being able to detail the final results to a greater extent, in addition to

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the possibility of being analyzed with greater knowledge of the area. In addition to this, obtaining the information has been simpler as a single autonomous community has been considered for administrative reasons, and due to the knowledge of the databases to be used to search for this information. The interpretation of the results shows that there is a very interesting area located in the geographical center of Cantabria, which obviously responds to the main groups of criteria: energy, geographic, and environmental aspects. It is a well-communicated area with a different climate from that in the south of Cantabria, where sunshine is undoubtedly higher, but temperatures are much more extreme, both in winter and summer. This goes against the simplistic thinking that the further south the better the area to locate solar plants, and fully validates the methodology developed.

6. Conclusions

Because it enables the examination and interpretation of georeferenced data, Multi-Criteria Analysis using Geographic Information Systems is a crucial tool for finding the best spot for a solar photovoltaic plant, and it solves complicated planning and land management issues. In order to find the most efficient spots to install renewable generation plants—in this example, solar photovoltaic plants—it is necessary to develop a methodology for determining these spots. This will make it much easier to identify potential areas for their installation. The research-based methodological proposal lays out the hierarchy of criteria to be considered in a multi-criteria analysis, how each criterion should be handled, and how to objectively weight these criteria, with the ability to check for consistency in the weighting process. This study provides a before-and-after comparison of the conventional methods, and these three areas constitute its primary contributions. An investigation of a particular area, like Cantabria, is carried out using the suggested technique. Based on this study, it can be said that the research proposal may be used to get a map of the country showing where a hypothetical factory would be most suited to be located. The criteria are defined in this proposal, followed by a system for their quantification. Finally, a weighing technique is established between the criteria, moving from a qualitative comparison to a quantitative one, and its consistency is checked. While the Saaty valuation method is less important, the research's primary contributions include a characterisation of time-dependent energetic or climatic criteria, a quantification of qualitative criteria or variables, a proposal for the number and selection of criteria, and so on. An alternative to using the average yearly temperature for classification is to use the average measurement value over three representative hours of the day. This makes it easier to adapt the criteria to how the variable actually behaves when the photovoltaic plants are in operation. By quantifying criteria, we can add characteristics like cloudiness in the study in a quantitative manner. We may also set criteria specifically for the target region to optimise plant performance. All things considered, the concept is novel in that it offers a weighing procedure that can be compared and contrasted using criteria that are distinct from all those that have been used in previous initiatives of a similar kind. The novel methodological idea is also universally applicable and amenable to extrapolation.

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