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Territorial Planning for Photovoltaic Power Plants using an outranking approach and GIS

Abstract

In 2015 the Paris Agreement set the goals for reducing greenhouse gas emissions. To achieve these objectives, it is necessary to boost electricity generation coming from renewable energy sources, particularly solar energy. Finding areas that are suitable for solar farm development is crucial for the economic feasibility of these projects and the sustainable use of land. This research investigates how to identify optimal sites for the development of solar plants. A GIS-based approach combined with a Multi-Criteria Evaluation methodology is used to create a map which shows a ranking of areas with high potential for solar farm development. The GIS-based methodology is employed in the treatment of the legal and environmental criteria and sub-criteria to delimit the suitable locations. These locations are evaluated and ranked by order using the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations). The importance of each criteria and sub-criteria is determined by an Analytic Hierarchy Process (AHP). In the Valencian Community the most discriminating criterion, when selecting the best locations, is the intensity of solar radiation, while temperature is the least discriminant. In terms of areas, the most suitable are located in the province of Alicante, while the least suitable are in the north of the Castellón province. It is also observed that the most appropriate locations are those that have greater solar radiation, and/or are at a lower altitude.

Highlights

- Geographic Information Systems (GIS) following a Multi-Criteria Evaluation approach provide a methodology to analyze the impact of PV power plants at a regional or local level.
- PROMETHEE has some advantages compared to other Multi-Criteria Decision Making (MCDM) methods:
  - it allows us to define a ranking of areas with high potential for solar farming,
  - to determine the contribution of each criterion to the aggregated index value for each particular area,
  - as well as which is the most discriminating criterion when identifying optimal sites, and which is the least.
- Policy makers can use the proposed method for the territorial planning of solar energy production activities in accordance with the national and European energy policy commitments.
- Investors have information in order to estimate a priori the economic results and to develop more and better PV solar projects.

Keywords

Solar farms, solar energy, grid connection, best sites, MCDM, GIS, AHP, PROMETHEE

Authors' consent to publish

By submitting this abstract to the Journal of Cleaner Production, the authors declare that the material is original and has not been published elsewhere. They also agree that it can be included for publication in Journal of Cleaner Production.

1. Introduction

The 2015 Paris Agreement, based on the scientific consensus of climate experts from around the world to combat climate change, set the goals for reducing greenhouse gas emissions. But to achieve these objectives and thereby the electrification of the global economy, there must be a transition towards a sustainable, safe and competitive energy system which replaces energy production by non-renewable resources with renewable and non-polluting ones.

This energy transition will require tools to reform the electricity market, as well as new energy planning tools and new electricity management systems for the desired goals to be achieved.

The European Union (EU) agreed that by 2030, 32% of the total EU energy consumption should come from renewable energy (the original target of 34% having been lowered). Consequently, for these objectives to be achieved, different directives have been issued to implement actions in this field. However, on the basis of the review of policies undertaken by the EU in 2018, these actions would only reduce greenhouse gas emissions by 60%, which is not sufficient to reach the Paris Agreement objectives ((EEA), 2016)) (Concil of The European Union, 2018).

The recent revision in November 2018 of the European strategy for cutting emissions established that 80% of electricity in 2050 should come from renewable resources. Nevertheless, there are some European countries, such as Spain, that cannot guarantee that 20% of their energy will come from these types of resources in 2020, as set by the current EU directives. The installation of new renewable energy power stations has therefore become crucial to be able to face the growing energy demand of the 21st century, whilst meeting the global climate objectives (Kumar, et al., 2017). Consequently, energy planning must guarantee that these power plants are effectively and efficiently managed from both a technical and economic point of view. Their management must be effective so that the energy production and emission reduction objectives can be met and also efficient as they must be competitive in terms of cost, thereby contributing to solving the current problem of expensive energy production, which produces negative social effects such as energy insecurity and energy poverty.

To be able to attract the necessary capital to invest heavily in renewable energy and networks, adequate energy policies together with clear and stable predictable regulations are required. Specifically, the renewable energy resources with lower costs and greater potential are those produced in wind energy and photovoltaic (PV) plants (Simao, et al., 2009; Cavazzi & Dutton, 2016; Trappey, et al., 2016). Both these technologies have seen their investment costs significantly reduced thanks to the level of maturity reached in these technologies. The last report by the International Renewable Energy Agency (IRENA, 2018) predicted that in 2020 production costs incurred by wind or solar PV energy plants would be lower in comparison to those of systems which use fossil fuels.

A considerably important factor in the development of this type of power plants is the large amount of land needed (solar farms are large grid-connected PV systems which have an installed capacity of more than 100 kWp and cover approximately 500 square meters) (Graebig, et al., 2010; Perpiña Castillo, et al., 2016) and the weight of this factor has grown in the total costs of the investment, whereas the cost of this technology has decreased. Therefore, finding areas that are suitable for solar farm development is crucial to the economic feasibility of these projects and the sustainable use of land. Previous work in this area has studied solar resource availability (Šúri , et al., 2007), but there are few studies on territories with renewable energy potential and even fewer which deal with solar farm potential (Sánchez-Lozano, et al., 2016; Yushchenko et al., 2018). The rational and sustainable use of irreproducible natural resources such as land make it necessary to develop land-use plans which allow these resources to be used in a planned, sustainable and appropriate manner (Akıncı et al., 2013; Kumar et al., 2017).

What strategic renewable energy planning does, particularly solar energy planning approaches, is to study the impact of solar farms at a regional or local level, and to identify areas having suitability and availability to be developed as solar farm.

An important part of solar energy planning is the determination of the factors or criteria that affect the solar resource in terms of magnitude and also the financial viability of solar farm projects. In this planning, therefore, it is essential to consider political, social, economic and environmental criteria (Joerin et al., 2010; Kumar et al., 2017; Yushchenko et al., 2018).

Multi-Criteria Decision Analysis (MCDA) has been proven to be one of the best tools for efficient energy planning (Kumar, et al., 2017). It includes various technical methodologies which can be applied in the evaluation and design of energy planning based on the optimization of either single or multiple criteria.

Many countries have already implemented new governmental policies to transform their current energy systems, setting an example for other countries to follow. However, new contributions are continually needed for the design of new planning policies.

The objective of this study is to provide a new approach that can contribute to the development of renewable energy generation, minimize environmental impacts and avoid dependency on fossil fuel supply.

Different studies on territorial planning have combined Geographic Information Systems (GIS) with MCDA in order to carry out a step-by-step decision making process to resolve conflicts about land use, which commonly appear during territorial planning processes. A review of the agricultural literature shows that there are numerous examples of the combined application of multi-criteria evaluation and GIS in the planning of agricultural activities (Mendas and Delali, 2012; Akıncı et al. 2013; Zabihi et al., 2015; Hajdinger & Tadic, 2019). There are also examples in the environmental field regarding decision-making for landfill locations (Nas et al., 2010) and the restoration of protected areas (Nekhaya et al., 2009; Morinha et al., 2017). Recently, quite a few authors have also used the combination of GIS-MCDA methods to select appropriate locations for developing renewable energy-based plants (Al Garni, et al., 2018; Yushchenko et al., 2018; Firozjaei, et al., 2019; Doorga, et al., 2019), and specifically for solar farms (Sanchez-Lozano, et al., 2016; Perpiña Castillo, et al., 2016). In line with some of these approaches, the aim of this research work is to integrate Geographic Information Systems (GIS) with a Multi-Criteria Evaluation Approach (MCDA) to provide a methodology that analyzes the impact of photovoltaic (PV) power plants at a regional or local level and allows us to construct a map which classifies the areas studied and identifies those with high potential for solar farm development. In previous research works with a similar objective, other MCDA methods such as Ideal Solution (TOPSIS) and Elimination and Choice Expressing Reality (ELECTRE) (Sánchez-Lozano et al., 2016) or Ordered Weighted Averaging (OWA) (Perpiña Castillo, et al., 2016; Yushchenko, et al., 2018) are employed.

In this study we propose the multi-criteria evaluation approach Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) to analyze and rank the areas with high potential for photovoltaic energy production. This method, developed by Brans in 1984 (Brans, 1984; Brans and Vincke, 1985), is one of the most known and widely applied outranking methods. It follows a transparent computational procedure, can be easily understood by decision makers who are unfamiliar with these techniques and can be adapted for use in groups of decision makers (Georgopoulou, Sarfidis, & Diakoulaki, 1998).

Indeed, to date, the PROMETHEE method has been used only to a certain extent with different approaches that present a few weaknesses and shortcomings when analyzing sites for solar farm development (Wiguna et al., 2016) (Samanlioglu and Ayaâ, 2017). PROMETHEE has been used particularly for the assessment of solar power plant location alternatives, but without carrying out a GIS selection process beforehand. Consequently, only a limited number of location alternatives could be analyzed, specifically four, and these were previously selected without any factor analysis in order to determine the best locations (Samanlioglu and Ayaâ 2017)). When undertaking territorial solar planning, a methodology is needed that allows us to analyze a given territory and to elicit information about the best locations at a regional or local level, therefore guaranteeing the economic feasibility of the solar power plant projects and the sustainable use of land. Although Wiguna et al. (2016) use GIS, they do so with a small number of criteria and do not rank the areas.

PROMETHEE offers some advantages as compared with other methods: a) it provides a complete ranking of alternatives, thus all alternatives are comparable; b) standardized variables are not required, which actually reduces subjectivity even more during the selection of criteria; c) it enables us to convert the (quantitative or qualitative) ratio scale measures of the categories corresponding to each criterion into comparable values; d) it offers information about the conflicts between criteria and allows for sensitivity analysis in order to observe the impact of the weights on the solution; in this way, it is possible to aggregate the criteria values, which leads to an aggregated index that ranks the areas; e) when selecting optimal sites for solar farms, the hypothesis of a fixed trade-off rate between each pair of criteria is not realistic, and it is not advisable to use a methodology that allows an alternative to be selected in which the gain of good criteria could be compensated by the loss in other criteria which are not appropriate; consequently, non-compensatory methods such as PROMETHEE are necessary; f) PROMETHEE's non-compensatory outranking method is a more appropriate methodology (for our case) because in the resulting ranking each location alternative is valued according to how much it is considered better than others, i.e. it does not try to find good locations, but rather the best ones by taking into account the other locations; g) finally, it allows us to identify the contribution of each criterion to the aggregated index value for each particular area, as well as which criterion is the most discriminating when identifying optimal sites, and which is the least.

Rank reversal (RR) is a phenomenon that occurs when a decision maker, in the process of selecting an alternative from a set of choices, is confronted with new alternatives that were not thought about when the selection process was initiated (García-Cascales & Lamata, 2012). PROMETHEE, like other MCDA methods (e.g. AHP), is beset with the rank reversal problem. Several authors have already highlighted this problem in methods like the AHP (Saaty and Hu, 1998) or PROMETHEE (Mareschal et al., 2008) (Doan and De Smet, 2016). Regarding the AHP, Saaty argues that we should differentiate between the axioms established in the decision theory, where axioms must be strictly followed in all processes, and the learning and assessment processes of the decision process itself. He suggests that if new information is included in a decision problem, some of the axioms of the utility theory could be questioned. Another possibility suggested by this author is to consider the introduction of new alternatives in an analysis as new problems (starting the whole analysis process again without taking into account the previous results). Mareschal et al. (2008) show that RR can be restricted to specific situations and its effects can be somewhat mitigated. Doan and De Smet (2016) argue that from a theoretical point of view, rank reversal in PROMETHEE can only happen among alternatives that have close net flow scores, but that it can, in any case, still be used to handle large scale problems by sorting out the data.

Given that not all the criteria which affect solar land use are equally significant, it is necessary to know the weight of each criterion to be able to apply PROMETHEE. A particular weakness of PROMETHEE is that it depends entirely on the decision maker who assigns the weight to each criterion (Kumar et al., 2017).

There are a variety of approaches which can be applied to carry out this assignment process (Malczewski, 1999). PROMETHEE assumes a priori that the decision maker is able to weight the criteria appropriately, at least when the number of criteria is not too high (Macharis et al., 2012). Furthermore, it could be considered that all factors have equal importance, or a criteria weighting defined by us or by a decision maker through a simpler method of valuation, giving each criterion a weight according to a certain scale, could be used. However, this way, the results are influenced by the subjectivity of the author or the decision maker. An alternative method could also be the revised Simos procedure (Milani et al., 2008; Sánchez Lozano et al., 2015), but as with the other methods already mentioned, its results also depend on the author's or decision-maker's subjectivity. And if there are several decision makers, for instance when there is a wish to include the participation of experts, these methods fail to take into account the multiple preferences of stakeholders or experts. Consequently, the procedure of assigning weights in these allocation methods is especially complicated when the number of criteria is high.

Although it is impossible to say which method is best for estimating preferential weights, pairwise comparison methods do seem to be more robust with respect to other alternative methods (Romero, 1996).

Regardless of the process and method adopted to elicit preferences, these procedures have to be transparent, understandable and equitable in order to effectively facilitate a process of collaborative decision making aimed at achieving consensus. In this regard, the Analytic Hierarchy Process (AHP), developed in the late 70s by Thomas Saaty (Saaty, 1980), is a good method for implementing a transparent and collaborative procedure to elicit stakeholder views on the importance of criteria in solar planning. The following reasons can also be considered:

- AHP is perceived as a method that is as equally valid as others, but in terms of its performance, AHP is significantly preferred and perceived as easier to use (Macharis et al., 2012).
- AHP is a good mechanism for eliciting and aggregating preferences. Unlike other methods, AHP allows the preferences to be added or the priorities to be calculated by means of a preference matrix (in this case, of experts), in order to obtain the aggregate weights.
- It encourages differentiation between criteria to a greater extent than simple rating methods and reveals the inconsistencies in responses (Segura et al., 2015).
- AHP does not involve complex calculations (Kumar et al., 2017).
- AHP allows us to rank the criteria and also to establish the degree to which each criteria is prioritized with respect to the others.
- In order to attain a greater degree of objectivity in the weighting of criteria and to gain public participation in our analysis, criteria weighting was based on the opinion of a group of experts, which came from both the public and private sector, and also from industry and academia, and which were surveyed online.

Furthermore, it should also be taken into account that territorial planning processes affect the interests of many different social actors. The selection of various criteria requires the involvement of multiple actors such as experts, citizens of the community in question, government organizations, NGOs, etc. The current trend to democratize planning and decision-making processes implies that territorial planning cannot be undertaken by one person alone. For this reason, a different and alternative approach has been adopted in recent years, that of *participatory planning*, which pursues greater social involvement and the achievement of sustainable social and environmental development as a result of collective reflection. In order to gain effectiveness and efficiency in management, it is necessary to include certain basic elements in the planning such as reaching a consensus and social participation (Simao, 2014; Kumar et al., 2017; Yushchenko et al., 2018).

Additionally, the Geometrical Analysis for Interactive Aid (GAIA) plane has been used in this work to offer a graphical representation of the results showing the discriminating power of the criteria, the conflicting aspects and the quality of the alternatives in the different criteria.

This article makes two distinctive contributions. Our first contribution, which concerns the gaps in the energy literature, is an approach based on GIS, PROMETHEE and AHP methodologies to obtain a ranking of suitable areas for the installation of PV solar farms, thus providing a new approach for solving problems related to the development of PV plants and their spatial planning. Bearing in mind today's global concern about the effects of climate change, and that environmental commitments and policies are continuously reviewed and adjusted to new requirements and objectives in order to face the new energy challenges, energy planning is turning into an increasingly complex process where a multiplicity of factors must be taken into account. It is therefore necessary to continue researching and making novel methodological contributions that could be used as alternative tools with which to provide different solutions.

The second contribution of the article is an empirical application that shows how a theoretical model can be parameterized and used for identifying and classifying areas at regional level. We use this empirical application in our study to find optimal sites for solar farm development in a European region. The proposed approach is applied to the Valencian Community, a European region situated in the east of Spain.

The paper is divided into four sections. Section 2 provides information about the study area, the parameters or criteria used in the solar farm site analysis, and also about the methodology used, i.e. the three approaches, GIS, multi-criteria PROMETHEE and AHP, are described. Section 3 presents the results and the discussion. Finally, section 4 summarizes the paper's contents and provides some concluding remarks.

2. Methodology

Study Area

The study area, shown in Fig. 2, is the entire territory of the Valencian Community.

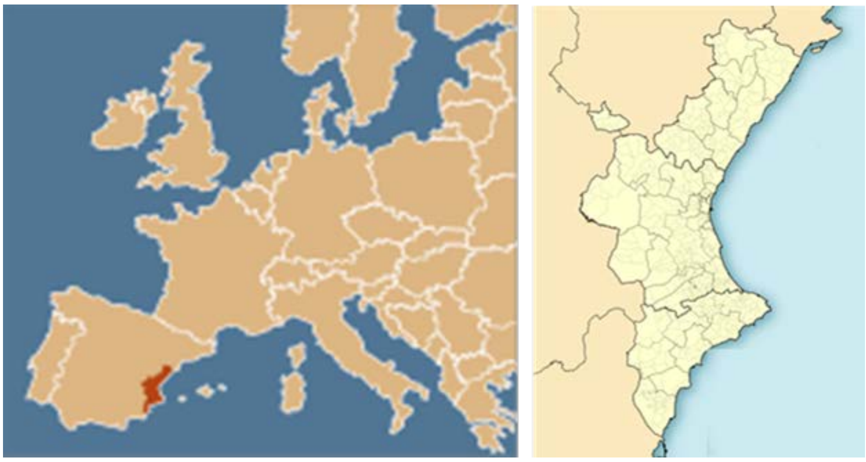


Figure 1: Study area: the Valencian Community

The Valencian region plays an important role in Spain’s economic development. It covers more than 23,000 km^2 and is located in what is known as the Mediterranean Corridor, a highly important economic area in Europe. Its current energy consumption stands at 23,000 GWh in 2018, with fossil fuels being the main source of energy (66%) and where renewable energy sources have barely been implemented. The Valencian Community is a region that consumes more energy than it produces, with a negative balance of approximately more than 2 GWh. The aim of the Valencian Government is to give preference to renewable energy sources rather than conventional ones, promoting actions which intensify their contribution to energy production in the region at the expense of fossil fuels. Although the main objective is to reach at least a 16% share of renewable energy in gross final energy consumption, the final goal is to achieve a greater use of renewable energy.

Selection process

The aim of this work is to provide a new approach to obtain a map of areas suitable for the development of PV solar farms using GIS and MCDA methods. As mentioned above, we propose the combination of GIS technology and multi-criteria decision-making techniques to select the most suitable areas for solar farm development. With this methodology, geographical data (criteria maps) and value judgments (decision-makers' preferences) are transformed and combined to obtain information for decision-making which is adequate and useful for spatial planning or the geographical distribution of activities, and also for the selection of optimal sites for these activities, particularly for the installation of solar farms or parks (Ocaña-Ocaña and Galacho-Jiménez, 2002; Fung and Wong, 2007).

How can available land in a region be distributed to organize its economic activities? Which types of solar plant projects can be implemented in the future? To be able to answer these questions, authorities must first make an assessment at a regional level and then develop land-use plans, thus allowing for resources to be used in a planned, sustainable and appropriate manner. Solar planning should also guarantee that these power plants are effectively and efficiently managed from both a technical and economic point of view.

Figure 2 shows a synthesis of the process. Through GIS spatial analysis, we first use restrictive criteria to eliminate those areas that are not suitable for solar power development and to identify the *not excluded areas*. Using a GIS-based approach for these areas once again, we then applied technical and environmental criteria to determine the *areas with high potential for solar farm development*. We followed this step because the previous selection of alternative locations did not give us information about their suitability compared to others, both in technical and environmental terms as well as in economic terms. Site selection involves screening the locations in order to select a limited number of suitable sites (alternatives) in a large geographic area.

However, these two selection procedures do not provide us with sufficient information about which of them is the best location. GISs only provide information without carrying out any type of analysis (Joerin et al., 2010).

It is therefore necessary to make a post-evaluation of the selected sites, in order to assess the alternatives identified in the previous screening. The PROMETHEE method allows the available areas to be ranked, while the AHP methodology helps to determine the weights of each criterion, which is necessary when using the PROMETHEE approach. Finally, a map is created that shows the results of the classification, i.e. a *ranking of areas with high potential for solar farm development.*

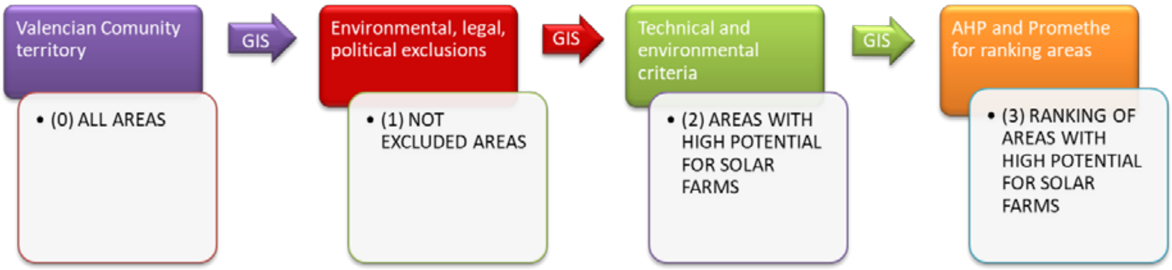


Figure 2: Selection process

Economic criteria could be applied to these areas to identify the *available geographical and economic areas*.

The steps followed to carry out this process are:

Step 1: Defining the criteria

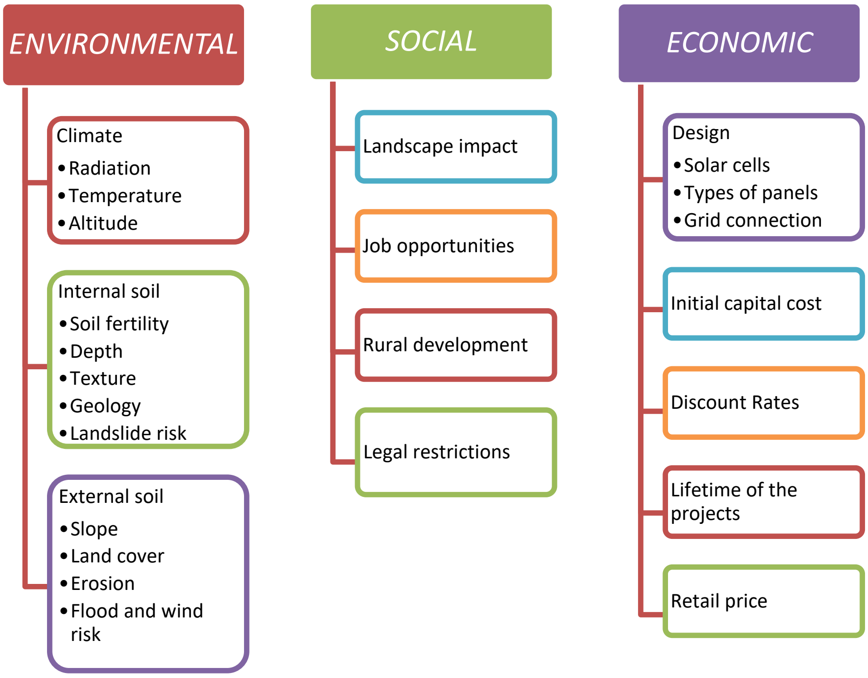
The first step is to select and determine the criteria, as well as the values of the criteria favorable to solar farm development. This analysis involves using restrictive criteria for solar power development, as well as a large amount of data regarding different physiographic factors, including climatic conditions, such as solar radiation, internal soil properties like natural fertility, depth, texture and geology, and external soil characteristics like slope, land cover, erosion, aspect, elevation, flood risk and accessibility. These criteria affect the solar resource in terms of magnitude and also condition the profitability of the land used for solar farm projects.

First, it is necessary to choose and define the evaluation criteria, while also determining their values for solar farm development. Based on the literature (Janke, 2010; Gastli and Charabi, 2010; Jo and Otanicar, 2011; Wang et al., 2016; Sánchez-Lozano et al., 2016; Yushchenko et al., 2018) and on the standards agreed upon by experts in solar PV farms, we define and draw up a list of criteria that affect the decision making towards one location or another. Political, social, economic, and environmental criteria are included in this list.

At a policy level, and with regard to energy planning, it is necessary to act upon urban planning, among other aspects, and also to foster sectoral planning formulated within the territory's space planning, which is the result of rational decision-making on the suitability of territories for specific uses and activities. In this study, the proposed analysis is framed within a regulatory framework of territorial planning. However, planning legislation may differ from one country to another, or even from one region to another. But for local or regional analysis, urban planning regulations provide a single regulatory framework for the entire study area, and thus legal restrictions can be incorporated into the social criteria.

Here, we selected up to 12 criteria and 15 sub-criteria, and grouped them according to their economic, social, and environmental characteristics. This classification is shown in Table 1.

Table 1: Criteria for identifying locations with high-potential for solar farm development



In addition, it is important to define the exact meaning of the criteria and their values (see also Table 5). Table 2 summarizes the information obtained from relevant literature on this subject for each criterion used in solar farm development. Most of the criteria were suggested by experts in previously published research, and additional criteria regarding environmental risks and geological criteria, which were proposed in some of our previous work, are also included (see references in Table 2). The table also shows how each criteria and sub-criteria are used to select suitable areas for solar farm development. If we consider the economic criteria, the initial capital cost of the development of solar parks in different optimal locations will be the same (EUR/m^2) for the type of installation considered, if the technology does not vary. The cash flows, or the revenue resulting from the installation, will be determined by income and costs. Both revenue and costs will depend on the production of electricity, which is related to radiation, and on the retail price. It should be pointed out here that, while the retail price is the same for all locations and is not a discriminatory criterion, solar radiation is.

Table 2: Description of the criteria for identifying areas with high potential for solar farm development

ESS	Selection	Review
1.- Environmental risks	Analyses of slip risk, soil detachment, or flood risk. Areas without risks are selected.	Guaita et al. (2018)
2.- Geology	Lithological analyses. Areas where it is easy to carry out excavations are selected.	Guaita et al. (2018)
3.- Protected urban soil	Urban soil classification analyses: residential areas, public domain areas, urban fabric, industrial and commercial sites, transport infrastructure, city parks, military areas. Areas where it is possible to implement solar PV farms are selected.	Šúri et al. (2007), Janke (2010), Gastli and Charabi (2010), (Sánchez-Lozano, Teruel-Solano, Soto-Elvira, & García-Cascales, 2013), Sánchez-Lozano et al. (2016), Wang et al. (2016)
4.- Land available	Analyses of nature areas of special interest: Birdlife Special Protection Areas (Special Protection Areas (SPAs), Sites of Community Importance (SCIs) and Special Areas of Conservation (SACs). Analysis of cultural sites: protected landscapes, sites of archeological interest, protected heritage sites, etc. Areas not included in the Natura 2000 network are selected. Areas without cultural sites are selected	Janke (2010), Gastli and Charabi (2010), Wang et al. (2016), (Sánchez-Lozano, Teruel-Solano, Soto-Elvira, & García-Cascales, 2013) Sánchez-Lozano et al. (2016)

ESS	Selection	Review
5.- Solar radiation	Radiation Analyses (1,100 and 1,330 kWh per installed kWp). Areas with a difference in yearly irradiation (kWh/m^2) OPT-HORIZ: 51-238 kWh/m^2 are selected.	Gastli and Charabi (2010), Janke (2010), Maleki et al. (2017), Suuronen et al. (2017)
6.- Accessibility	Analyses of access to land transport routes for maintenance and repair. Areas with access to regional or local roads are selected.	Janke (2010), Gastli and Charabi (2010), Maleki et al. (2017), Suuronen et al. (2017), Al-Ruzouq et al. (2018)
7.- Grid connection	Analyses of the distance to the nearest electricity network connection, the nearest power line, or transformer substation of electric power. Areas with a distance of less than 1,500 meters from these sites are selected.	Song et al. (2015), Wang et al. (2016), Maleki et al. (2017), Suuronen et al. (2017)
8.- Slope and orientation	Analyses of terrain flatness. Areas with a gradient below 5% and with south-east orientation are selected.	Šúri et al. (2007), Chiabrando et al. (2009), Gastli and Charabi (2010), Wang et al. (2016), Suuronen et al. (2017), Maleki et al. (2017), Al-Ruzouq et al. (2018)
9.- Land cover	Analyses of land with soil classified as coniferous and evergreen species (80%), deciduous trees (70%), growing citrus and other fruit trees (30%) olive and other woody crops (30%), vineyards (20%), arable farming, grassland, meadows (0%), market and kitchen garden, scrubland, bare soil land and burned areas (0%). Areas with a cover below 30% are selected.	Wang et al. (2016), Janke (2010), Maleki et al. (2017), Suuronen et al. (2017)
11.- Temperature	Analyses of the average temperatures measured by the AEMET weather station network. Areas with average temperatures of 10º C to 20º C are selected.	Skoplaki et al. (2008), Wang et al. (2016), Suuronen et al. (2017)
12.- Altitude	Analyses of the contour line map. Areas below 1,800 m are selected.	Skoplaki et al. (2008), Wang et al. (2016), Al-Ruzouq et al. (2018)

Source: By authors taking into consideration suggestions from studies focused on renewable energy planning.

The proposed analysis criteria are grouped into four levels of decision (Figure 1). The first level is determined by the current legal framework and environmental criteria that preclude the installation of solar farms (geological criteria, flood and landslide risks, etc.). It is in this decision level that the areas for the construction of these types of power plants are identified. The areas are selected according to regulatory decisions made by the government with competences in the territory under study (mainly the land classification in the region) (Šúri et al., 2007; Janke, 2010; Gastli and Charabi, 2010; Sánchez-Lozano et al., 2013, 2016; Wang et al., 2016; Yushchenko et al., 2018). For instance, it is not possible to build solar farms on populated areas, nature reserves and environmentally sensitive areas. Residential areas, public domain areas, urban fabric, industrial and commercial sites, transport infrastructure, city parks, and military areas are also types of land on which solar farm development is not allowed. In our paper we take into account the regulations imposed by the Spanish and Valencian governments, in compliance with the distribution of competences between the state and regional governments established by the Spanish Constitution.

At this decision level, it is also necessary to evaluate the areas according to geological criteria, in order to select the areas where it is easy to carry out excavations and to exclude those areas with flood and landslide risks. Accordingly, we apply criteria 1 to 4 to select those *areas not excluded*.

In the second decision level, we analyze the areas that are not excluded using criteria 5 to 12 so as to identify the *areas with high potential for solar farm development*. These requirements are necessary to ensure the normal functioning of solar plants and the production of solar energy.

Solar radiation refers to the electromagnetic radiation emitted by the sun and the expected average annual electricity generation. It is one of the factors that determines the economic performance of solar power systems. Solar radiation data related to solar electricity generation are used to assess solar farm development. In this regard, Šúri et al. (2007) have developed models to estimate solar radiation and average electricity generation. These authors identified regions with the highest potential for annual electricity generation from solar energy. Other authors (Gastli and Charabi, 2010; Janke, 2010) have also developed radiation models to select sites for solar farms. According to these studies, a minimum level of radiation is required for the installation of solar power plants. Furthermore, to minimize the costs of construction of PV infrastructure and its maintenance, this type of infrastructure has to be built on areas which are accessible. Thus, proximity to roads is another criterion to be considered. It is therefore advisable to carry out a previous analysis of the regional or local roads and select those areas which are accessible by road (Janke, 2010; Gastli and Charabi, 2010; Maleki et al., 2017). Proximity to the grid also significantly reduces transmission line costs and losses (Gastli and Charabi, 2010). Several authors recommend that solar plants are located at a distance within 1,500 meters from the grid system (Janke, 2010; Wang, et al., 2016; Maleki et al., 2017). Solar farms also require flat land or land with a gradient below 5% that is facing south or south-east orientation (Šúri et al., 2007; Chiabrando et al., 2009; Gastli and Charabi, 2010; Suuronen et al., 2017; Al-Ruzouq et al., 2018). Land cover or vegetation that increases shading is another criterion to be taken into account and it can be analyzed according to the crops or trees in the area. Land of low value, because of its past use (e.g. land with contaminated soil), which now has favorable conditions can be evaluated on its potential for solar farm development. Land with evergreen tree species, deciduous trees, citrus and other fruit trees, and olive and other woody crops, have a high land cover and are not considered suitable sites for solar farm development. On the other hand, vineyards, arable farming land, grassland, meadows, market and kitchen gardens, scrubland, bare soil land and burned areas are interesting sites for solar farm development (Janke, 2010; Wang et al., 2016; Maleki et al,. 2017; Suuronen et al., 2017). Temperature affects the efficiency of solar cells for electricity generation, because it plays a central role in the photovoltaic energy conversion process. Similarly, higher altitude hinders the construction of PV power stations and electric transmission facilities. Certain studies recommend disregarding areas with undesirable temperature and altitude conditions (Skoplaki et al., 2008; Wang et al., 2016; Al-Ruzouq et al., 2018).

Step 2: Geographic Information Systems (GIS) processes

The selection of areas with high potential for solar farm development using GIS requires the acquisition and management of spatial data, the application of spatial analysis, and the creation of map-based outputs (Simao et al., 2009).

The first part of this process is to obtain the thematic layers and maps concerning the exclusion criteria. GIS allow us to identify and order information in various layers of exclusion criteria and to store them in order to facilitate the generation of other layers which identify the available areas.

Figure 3 shows the topography of the Valencian Community which is characterized by an elevation that declines gradually from west to east, its maximum altitude being over 1,800 m. The solar radiation in this region is from a minimum of 51 kW/m2 to a maximum of 238 kW/m2. The highest solar energy densities occur in southern areas with more than 200 kW/m2. Hence, because of its abundance of solar energy, the Valencian Community has good potential to develop PV power stations.

In order to examine the study area, diverse geographic data from different data sources available in various formats (see Table 3) is used, i.e. maps from the Valencian Institute of Cartography (ICV), the National Geographic Institute (IGN). The Valencian Institute of Cartography has an important set of maps available, which includes comprehensive information on the relevant spatial criteria for the selection. The maps available show environmental protected areas, high mountain and forest areas, or rich land suitable for agriculture. In addition, there are maps with infrastructure data containing the high and low-voltage power lines of the Valencian Community. The maps of the National Geographic Institute were also employed for this research. The solar radiation layer and temperatures were obtained from the PVGIS (Photovoltaic Geographical Information System) website of the European Commission and from the Spanish National Weather Service (AEMET). We used all this information to determine the most suitable parameters for selecting the optimal sites for the construction of solar PV farms.

Figure 3: DEM and solar radiation in Valencian Community

Table 3: Georeferenced data layers

	Data	Format	Scale	Publication date
Digital elevation model**	5m-resolution DEM in the VC	Raster	------	2010
Official cartography of the Valencian Community**	Transport Network	Shapefile (vector format)	1/5,000	2014
	Services and Facilities			
	Administrative boundaries			
Urban planning***	Urban classification	Shapefile (vector format)	1/25,000	2018
Risk cartography***	Flood risk. Territorial Flood Risk Prevention Plan (PATRICOVA)	Shapefile (vector format)	1/25,000	2015
	Landslide risk		1/50,000	1991
Photovoltaic Geographical Information System	Solar radiation databases: average radiation both day and night measured in W/m^2	Raster	------	2005-2015
SIOSE	Spanish Land Cover and Use Information System	Raster	1/25000	2005-2015
Green infrastructure	Influence areas of wetlands in the Valencian Community (VC)	Shapefile (vector format)	1/5,000	2002
	Wetlands of international importance in the VC		1/5,000	2002
	Special Areas of Conservation (SAC) in the VC		1/25,000	2013
	Birdlife Special Protection Areas in the VC		1/10,000	1992 (updated in 2009 with 25 new areas)
	Natural Monuments Buffer Zones in the VC		1/5,000	2007
	Nature Reserves in the VC		1/5,000	2011
	Protected Landscapes in the VC		1/5,000	2007
	Nature Parks in the VC		1/5,000	2007

🟧	Local nature sites in the VC		1/5,000	2002
	Sites of Community Importance in the VC		1/50,000	2001

Source: *Valencian Government, Regional Department for Agriculture, Environment, Climate Change and Rural Development; **Valencian Institute of Cartography; ***Valencian Government, Regional Department for Housing, Public Works and Territorial Planning.

The initial databases are combined into one table and an event theme is created. From there, a shapefile in point format is created, which is used as the object of analysis in this study. First, the layers referring to environmental, legal and political criteria data are obtained (see criteria 1 to 4 in Table 2) to create the map of areas not excluded. The Valencian Community has several of these areas.

In the next stage, using GIS to analyze the technical and environmental variables of the *not excluded areas,* we identify those areas which are suitable for the location of solar farms (see criteria 5 to 12 in Table 2). Work is carried out in the same way as in the previous stage. From georeferenced data contained in different layers which are superimposed, we identify the areas that comply with the technical and environmental conditions considered suitable, or those areas with high potential for the development of solar farms.

Figure 4 provides a flow diagram with the site selection process whith GIS to select *high potential areas for solar farms.* The layers with geographical data on excluding criteria (*risk areas, urban land use* and *urban protected land*) are overlaid to obtain the map of excluded areas and are removed from the total study surface (Valencian Community layer) to be able to determine the *not excluded areas*. Next, the layers containing technical and environmental criteria (*slope, orientation* and *land cover*) are overlaid and their distance to the elements of the layers with location criteria is calculated. In this step, the layer of areas with the most favorable distance conditions is obtained. Finally, this layer is intersected with the not excluded areas layer to determine the areas with high potential for solar farm development.

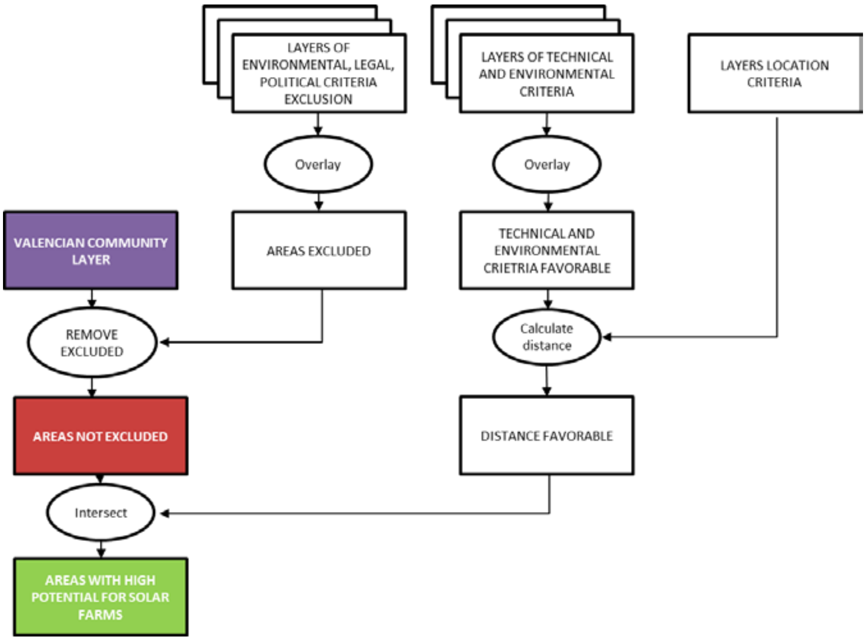


Figure 4: Methodology used to select areas by GIS

The different areas are considered spatial entities, i.e. polygons in the vector model and grid cells in the raster model, and constitute location alternatives ($a_1, a_2, a_3, \ldots, a_n$). Each of these entities adopts a value (xji) for each criterion (j=1, 2,…m entities; i=1, 2,…n criteria).

Step 3: Weighting of the criteria using AHP

In our study we use different criteria to select suitable areas for solar power development. In decision making processes, criteria are often assigned weights depending on their relative importance. Integrating the maximum number of criteria for evaluating areas and finding their relative weights is a very complex matter. Weights can differ due to the different characteristics of the location in question, the point of view of the different evaluators and the data available. Therefore, the resulting classification of areas depends on the choice of factors and their weights (Yushchenko et al., 2018).

The AHP methodology, is an excellent and widely used Multiple Criteria Decision Analysis method (MCDA) designed to solve the problem of how to assign weight to a set of different criteria according to their importance. On the one hand, with this method we aim to solve (as objectively as possible) the problem of subjectivity inherent in decisions made by decision-making agents regarding land use. On the other hand, through the consultation with experts we can also incorporate the social preferences that go with these types of complex decision-making processes, where there are many variables or criteria to be considered. Thus, the use of the AHP methodology is especially interesting for spatial planning because of the opportunity it provides for developing a participatory decision-making process (Saaty, 1980).

Figure 5 illustrates some of the steps that AHP involves:

Modelling: hierarchical representation of the decision problem

Decision makers (stakeholders) **carry out pairwise comparisons** of the criteria

Synthesis and calculation of the results to obtain the criteria **priorities**

Figure 5: Analytic Hierarchy Process

Modelling involves creating a hierarchical representation of a decision problem with all the relevant aspects. The basic hierarchy consists of a goal or overall objective, which is the decision problem, and the criteria, which are the elements that affect the decision. They are organized according to levels where the main criteria, which would be on a previous level to the overall objective, and the sub-criteria for each of the main criteria can be distinguished. As described above, the criteria 5 to 12 in Table 2 are grouped into categories of location, characteristics of external soil, and climate, which can be seen in Figure 6.

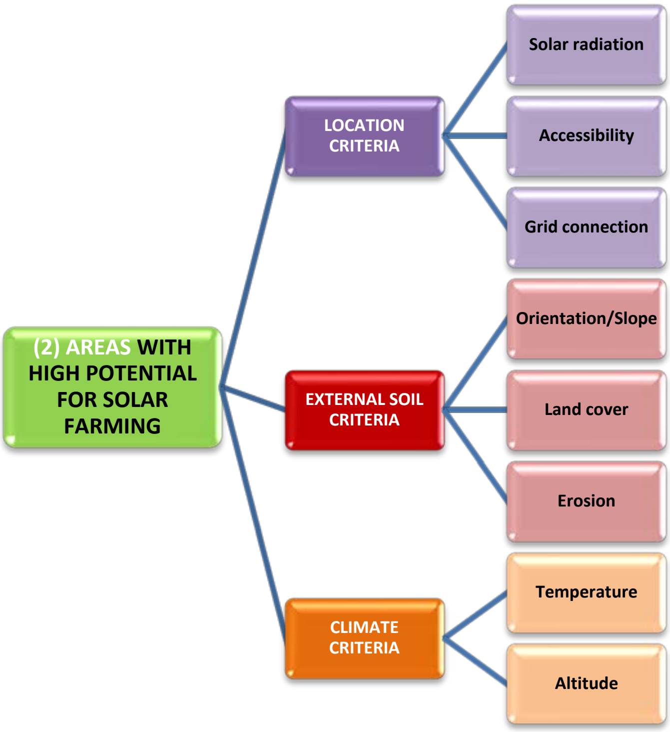


Figure 6: Hierarchy for the selection of solar farms locations

In the following stages, decision makers carry out pairwise comparisons of the criteria on each level of the hierarchy. The pairwise comparison allows the decision maker to express his/her preferences and quantify the intensity with which one criterion is preferred over another, using the measurement scale proposed by Saaty. This scale not only enables the decision maker to incorporate his/her subjectivity, experience and knowledge, but is also theoretically justified, and its effectiveness has been empirically validated (Martinéz, 2007).

A group of experts was invited to participate in an online survey (https://goo.gl/forms/fttkGysFBBIx979Q2). The group constituted a representative sample of various fields related to the analysis. Invitations to participate in the survey were sent to staff and faculty from research centers and universities who work in the field of renewable energy research, more specifically of solar energy, and to professionals of the sector who were members of associations and organizations related to the production of renewable energy. We assume that all the members of the group have the same importance in the decision-making process.

Each member makes a judgment as to which criteria is more important and decides how much more important it is. The judgments are then translated into numerical values using the 1-9 Saaty scale (Saaty T. , 1980). When the group is not very large, one way of obtaining a single set of judgments from the group is by debate and consensus of the comparisons of each criteria and sub-criteria. If there are a lot of criteria and subcriteria, and there is a great deal of comparisons to be made, then the consensus process becomes complicated. If agreement is not possible, then each individual must solve the problem independently. Next, by aggregation, the priorities for the group are calculated. von Solms and Peniwati (2001) question whether an aggregation method should be used or not. They conclude that reaching consensus only makes sense in unitary contexts, which is the case only for a small minority of real-world decisions. In most cases, particularly if wide participation in encouraged, the decision-making context will be pluralist. In these cases, the recommendation is to seek alternatives for aggregating the individual judgments using, for example, the geometric mean. In this way, the aggregation results will better reflect the point of view of the group.

As a result of the comparisons of each criteria and sub-criteria, positive reciprocal matrices are obtained. A Saaty matrix was generated for each stakeholder, A_k, where a_{ij}, is the result the comparison between *criteria i* and criteria *j*:

$$A_k = \begin{bmatrix} a_{11} & a_{12} \dots & a_{1n} \\ a_{21} & a_{22} \dots & a_{2n} \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} \dots & a_{nn} \end{bmatrix} \qquad [1]$$

Using the matrices with the individual preferences, the priorities of each stakeholder were calculated according to the various functions and following the Eigenvector Method (EM): the vector of weights is the eigenvector corresponding to the maximum eigenvalue λ_{max} of the matrix A.

$$\mathrm{A} \times \mathrm{W} = \lambda_{\max} \times \mathrm{W} \qquad [2]$$

where:

W= priorities vector or vector of weights

$\lambda_{\max}$ = maximum eigenvalue of the matrix

The resulting priorities are:

$$W = (w_1, w_2, \dots, w_n)^k \qquad [3]$$

Forman and Peniwati (1998) consider that when interviewees act according to their own criteria and with different value systems, we should take into account the priorities of each one, and that individual priorities should be aggregated rather than preferences. Based on these recommendations, we aggregate the individual priorities AIP approaches to be able to calculate the stakeholder group priorities together with those of the individuals in the sample group.

$$W = [w_i] = \sqrt[m]{\prod_{k=1}^{m} w_{im}} \qquad [4]$$

$$w = (w_1, w_2, .., w_n)$$

Where:

m: number of stakeholders

Not all comparison matrices are included in the results. Coherence in each interviewee's preferences was checked based on *individual consistency*, which should be taken into account when considering whether individual opinions are valid for determining the group priorities. Consistency analysis requires the calculation of the *consistency index* (*CI*) of Saaty for each preference matrix.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad [5]$$

The *consistency ratio* (*CR*) is calculated from *CI*. *CR* is a ratio between *CI* and *RI*:

$$CR = \frac{CI}{RI} \qquad [6]$$

where *RI* is the average value of *CI* of the pairwise comparisons matrices of the same order randomly obtained. When CR is less than 10% (0.1), it is considered that the matrix has an acceptable consistency level.

Step 4: Ranking of location alternatives using PROMETHEE

We identified the location alternatives (a1, a2, a3, …, an) by using GIS. Each alternative location or area adopts a value (x_{ij}) for each criterion. The aggregation of values determines the way in which the areas are classified and ranked in order of suitability. We use PROMETHEE to aggregate the values and classify the areas. Its use has been limited by the fact that it cannot be applied to long series of data due to limitations of computer systems. Until recently, PROMETHEE was used in spatial planning only for the study of fairly small areas. However, at present, software developments such as D-Sight already allow large areas to be studied at a regional or larger level, as demonstrated in this work.

PROMETHEE allows a ranking of possible location alternatives (a_1, a_2, a_3, …, a_n) to be created, based on the defined criteria (5 to 12 in Table 2). For the application of the PROMETHEE methodology, the criteria are grouped into categories of location, external soil characteristics, and climate, as shown in Table 4, (L_1, L_2, L_3, ExS_1, ExS_2, Cl_1, Cl_2.

Table 4: Model matrix of location a_j alternatives for the application of the PROMETHEE methodology

Alternatives	Criteria						
	LOCATION CRITERIA			EXTERNAL SOIL CRITERIA		CLIMATE CRITERIA	
	Solar radiation	Accessibility	Grid connection	Orientation/ slope	Land cover/ Erosion	Temperature	Altitude
	L_1	L_2	L_3	ExS_1	ExS_2	Cl_1	Cl_2
	Max	Min	Min	Min	Min	Max	Min
a_j							

In the PROMETHEE methodology, the preference structure is based on pairwise comparisons. What is different is that the comparisons are based on the difference between the evaluations of the alternatives for each criterion. The greater the difference, the greater the preference for the alternative that behaves better, represented by real numbers between 0 and 1. Value depends on the function of preference used and is the mechanism that allows us to integrate, in a single indicator, the different criteria measured in different units. For each criterion, a preference function must be proposed. The most used preference function types are the following: usual, U-shape, V-shape, level, linear and Gaussian (Table 5).

Regarding the degree of preference of an alternative, a_1, over another, a_2, for the same criterion *j* (L_1, L_2, L_3, ExS_1, ExS_2, Cl_1, Cl_2), the decision maker must choose a preference function $P_j(a_1, a_2)$, which depends on the difference between the behavior of the alternatives:

$$P_{L1}(a_1,a_2) = F_{L1}[L_1(a_1)-L_1(a_2)]=F_{L1}[d_{L1}(a_1,a_2)] \qquad [7]$$

where:

d: is the difference between the behavior of the alternatives for L_1 criteria

If we want to maximize the criterion, the preference will be a_1 over a_2 if the difference is positive, and zero if otherwise. But if what we want is to minimize the criterion, it would be the contrary.

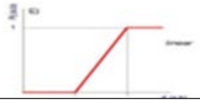
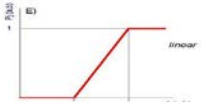
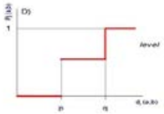
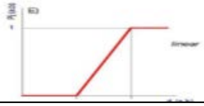
Preference functions are available within D-Sight, a decision-making software that implements the PROMETHEE and GAIA (Geometrical Analysis for Interactive Aid) methods developed at the Université Libre de Bruxelles.

For all the preference functions, except for the *usual* type one, one or two parameters must be defined, depending on the case: the indifference threshold (q), the strict preference threshold (p) and an intermediate value between both (s).

The indifference threshold is the difference between the evaluations of the two greatest alternatives which is considered as negligible by the decision maker**.** The preference threshold is the difference between the two smallest alternatives, which is considered sufficient for one of them to have a strict preference over the other. In the Gaussian type function, a value between the indifference threshold and the strict preference threshold must be established.

Table 5 shows the functions established for each criteria and their treatment for the application of the PROMETHEE method. The selected values in Table 5 are determined on the basis of available datasets and the literature review.

Table 5: Assignment of the preference functions for each criteria

ESS	Selection	Function Type	Shape	Unit	min	max	p	q
Annual average solar radiation	Analyses of radiation (1100 and 1330 kWh per installed kWp). Areas with a small/big difference in yearly irradiation are selected (kW/m2) OPT-HORIZ: 51-238 kW/m2	Linear/Increasing		*KW/m²*	51	238	0	187
Accessibility	Areas with access to regional or local roads are selected	Linear/Decreasing		*m*	0	500	0	500
Grid-connection	Analyses of the distance to the nearest electricity network connection. Areas with a distance of less than 1,500 meters are selected	Linear/Decreasing		*m*	0	1,500	0	1,500
Slope	Analyses of the terrain flatness. Areas with a gradient below 5% are selected.	Linear/Decreasing		*%*	0	5	0	5
Orientation	Analyses of the deviation from the geographical North. Areas with south-east orientation are selected.	Linear/Increasing		*(°)*	45	230	0	185
Land cover	Analyses of soil classified land. Areas with a cover below 30% are selected.	Level		*%*	0%	30%	0	30%
Temperature	Analyses of average temperatures measured by the AEMET weather station network. A temperature higher than 25ºC tends to reduce the PV efficiency. Areas with average temperatures between 10º C and 20º C are selected.	Gaussian/symmetric		ºC	10ºC	20ºC	0	10ºC
Altitude	Analyses of the contour line map. Areas lower than 1,800 m are selected.	Linear/decreasing		*m*	0	1,800	0	1,800

PROMETHEE allows us to assess thousands of alternatives. However, it is not possible to build solar installations on every part of the territory since a minimum surface area is required for the installation of solar plants. On the other hand, in view of the numerous forecasts predicting an increase in PV implementation in certain countries or regions (REN21), territorial planning has become an essential tool for organizing these activities in a given territory, which will help identify the areas in which to locate these installations. As a result of the previous analysis of the territory using GIS, there is a finite number of location alternatives where it is legally, technically and environmentally feasible to install solar plants. From a geometric point of view, each alternative or defined zone is a polygon that contains different values for the same criterion (all within the range of values suitable for the installation). To solve this problem, we could consider that the value assigned to each criterion in each alternative area is the mean value of all the values possibly taken by one criterion within each polygon, which represents an alternative area.

To be able to implement the PROMETHEE method, information is needed on the relative importance of the criteria, as their weight (w_1, w_2, ... w_n) must previously be established through the AHP method. With the help of an evaluation matrix, the weights of each criteria and the preference functions chosen for each one of them, we calculate the *aggregate preference indices* for each pair of alternatives a_1 and a_2, which are the degree of preference of alternative a_1 over a_2, and vice versa.

$$\pi(a_1 a_2) = \sum_{i=1}^{n} P_i\ (a_1 a_2) w_j\ [8]$$

$$\pi(a_2 a_1) = \sum_{i=1}^{n} P_i\ (a_2 a_1) w_j\ [9]$$

Based on the aggregate preference indices of each alternative with respect to each one of the other alternatives, we calculate the positive and negative outranking flows. From these flows we can then create a partial ranking of the alternatives, from which we can conclude whether an alternative a_1 is preferable, indifferent or incomparable to another alternative a_2.

Step 5: Economic analysis for the ranking of locations

In steps 2 to 4, we have applied the environmental, technical, and economic criteria listed in Table 2 in order to obtain the areas with the highest potential for solar farm development, and we have arranged the areas in ranking order. This order is the result of the criteria and technology considered.

The fact that we also consider economic criteria (such as initial capital cost, cash flows, discount rates, and retail prices, as proposed in Table 1) represents an additional level of decision-making, through which financially sustainable locations can be found.

Regarding the economic variables, the initial capital cost of the installation of solar parks in different optimal locations will be the same for the type of installation considered, if the technology does not vary. The only discriminating variable will be the price of land, which can be included as the annual rent to be paid. The cash flows will depend on the receipts and payments generated by the solar installation. Operation and maintenance costs for the solar installations are predicted to be similar in the different locations, but not so the land rental, which will depend on the location. Revenue will depend on the amount of electricity produced in each location, and on the retail price, which will be the same for all sites. According to the ranking provided by PROMETHEE, the locations with a higher aggregate index and, therefore, the better ones, are also those with a higher intensity of solar radiation. Thus, location is the most discriminating factor as to the ranking order.

Nevertheless, as pointed out before, an important variable for the development of solar installations is the large amount of land needed, since, in our case, the land price of specific Mediterranean coastal areas is a significant factor which shapes the economic performance of these installations.

An analysis of land value in the Valencian Community for the proposed sites allows us to carry out a sensitivity analysis of the land value and its impact on the location of the solar installations which could alter the previous ranking due to financial reasons. This change in the order would only occur if the difference in the land rental between two consecutive locations is higher than the difference between the predicted incomes for these locations. The sensitivity of the result should be tested regarding the variation of some of the variables that shape the investment, specifically the variation in net cash flows, when the price of land changes, in order to assess its effect on the ranking of the best locations.

3. Results and discussion

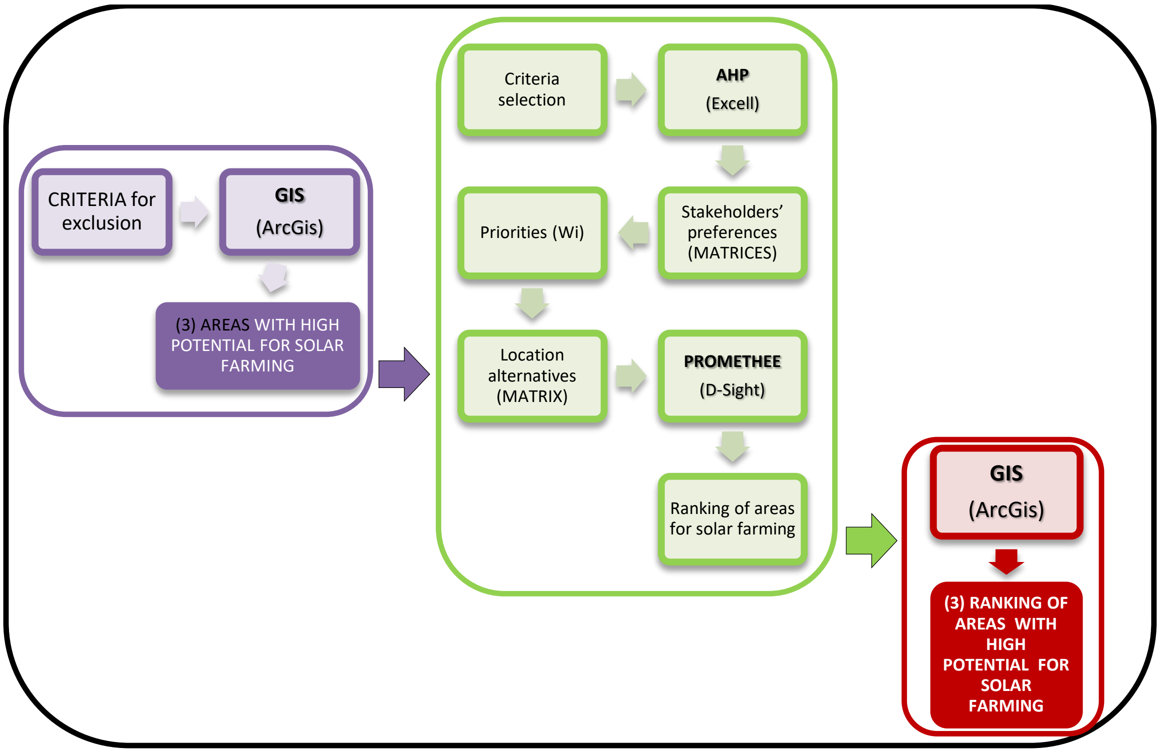


Figure 7: Evaluation process of the areas

Based on the evaluation process by GIS of the area studied (Figure 7), we define the *areas with high potential for solar farm development* (Figure 8). The result is 77 alternative areas with a surface of 5 ha, and 22 alternatives of 10 ha. For an area of 3-10 ha, an average electricity output of 1 MW must be set up (Mondal and Islam, 2011)(Khan and Rathi, 2014) (Guaita-Pradas I. et al, 2015). As a spatial planning tool that contributes to the organization of activities in the territory, we propose the selection of areas with a surface area greater than 10 ha. The resulting 22 zones in the study area are polygons with a surface of between 10 and 50 ha, which are located in different zones of the Valencian Community (Figure 8).

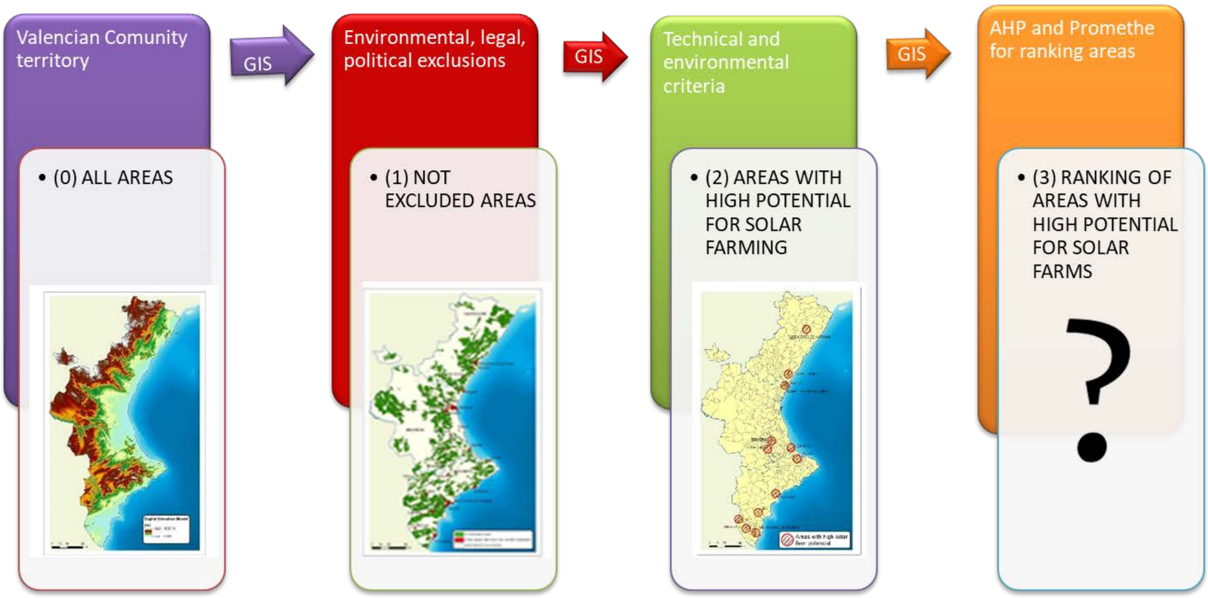


Figure 8: Selection process

Thirty-three experts from the renewable solar energy sector completed the on-line survey. As a result, twenty-three matrices were completed by experts from research centers and universities, and ten from professionals of the sector who were members of associations and organizations related to the production of renewable energy.

The weights of the criteria and sub-criteria (Figure 6) resulting from the application of the AHP method are shown in Table 6.

Table 6: AHP results (weights: w)

w LOCATION CRITERIA	0.408	
w Solar radiation	0.501	0.205
w Accessibility	0.143	0.059
w Grid connection	0.355	0.145
w EXTERNAL SOIL CRITERIA	0.189	
w Orientation/Slope	0.757	0.143
w Land cover	0.243	0.046
w CLIMATE CRITERIA	0.403	
w Temperature	0.747	0.301
w Altitude	0.253	0.102

The aggregation of matrices shows that location criteria and climate criteria are the most important factors when considering appropriate sites for solar farm development (Table 6). Temperature and solar radiation are the most important subcriteria, with 30.1% and 20,5% respectively. Land cover and accessibility are considered to be less important. The weightings for solar farm development led to a consistency ratio (*CR*) value of 8%, which is an acceptable consistency level.

We use these criteria weights to assess the alternatives by applying the PROMETHEE methodology to rank the *areas with high potential for solar farm development*.

Table 7: Location Alternatives a_j Matrix for the application of the PROMETHEE methodology

Alternatives	**Criteria**						
	LOCATION CRITERIA			**EXTERNAL SOIL CRITERIA**		**CLIMATE CRITERIA**	
	Solar radiation	**Accessibility**	**Grid connection**	**Orientation/ slope**	**Land cover/ Erosion**	**Temperature**	**Altitude**
	L_1	L_2	L_3	ExS_1	ExS_2	Cl_1	Cl_2
	Max	Min	Min	Min	Min	Max	Min
w_i	0.20	0.06	0.14	0.14	0.04	0.30	0.10
a_1	188.41	31	24	84.85	30	23	276.78
a_2	196.56	88	419	127.81	30	27	125.75
a_3	213.98	154	201	136.07	0	27	6.97
…							

Based on these results, an aggregate index of all the criteria is calculated, allowing us to determine which areas have a higher aggregate index, and thus establishing the areas which have the best conditions for the installation of solar farms. The higher the aggregate index, the better the alternative location is.

Figure 9 presents the ranking of the areas identified as suitable, while Figure 10 shows how each criterion contributes to each location.

Figure 9: Ranking of the PROMETHEE results

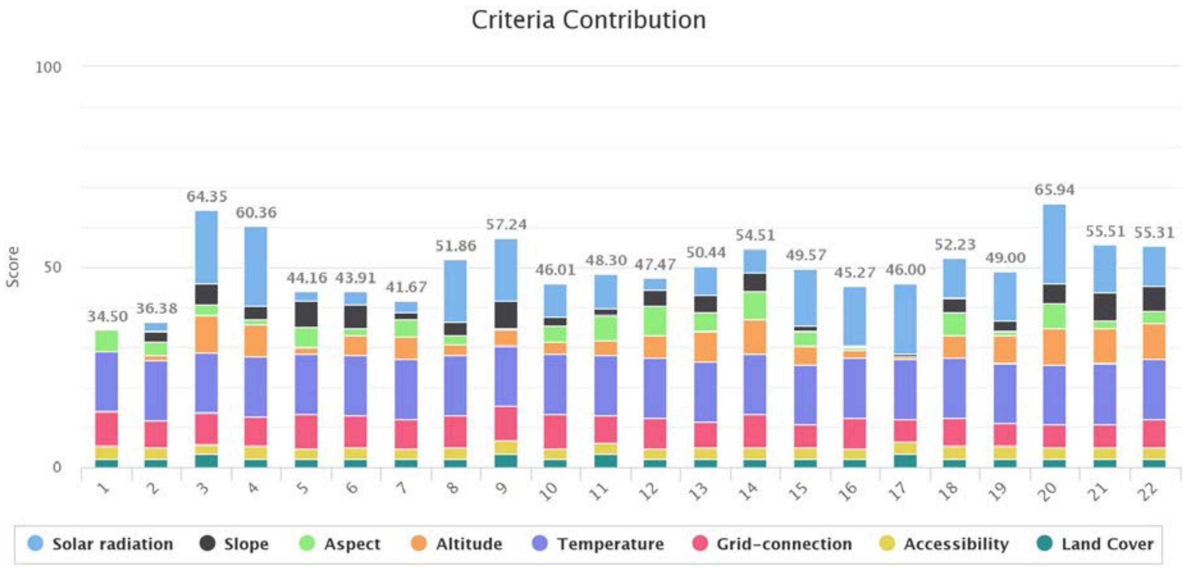


Figure 10: PROMETHEE results

The most suitable areas are located in the Vega Baja district, in the province of Alicante (location alternatives 20, 3 and 4). These are the areas with the highest aggregate index, i.e. higher than 60. The least suitable locations are in the north of the Castellón province (alternative 1, with an aggregate index of 34.5), and inland in the province of Valencia (alternative 2, with an index of 36.38). As can be seen from Figures 10 and 11, the most suitable locations are those that have a higher intensity of solar radiation, and/or are situated at a low altitude. Solar radiation is the most discriminating criterion, while temperature is the least.

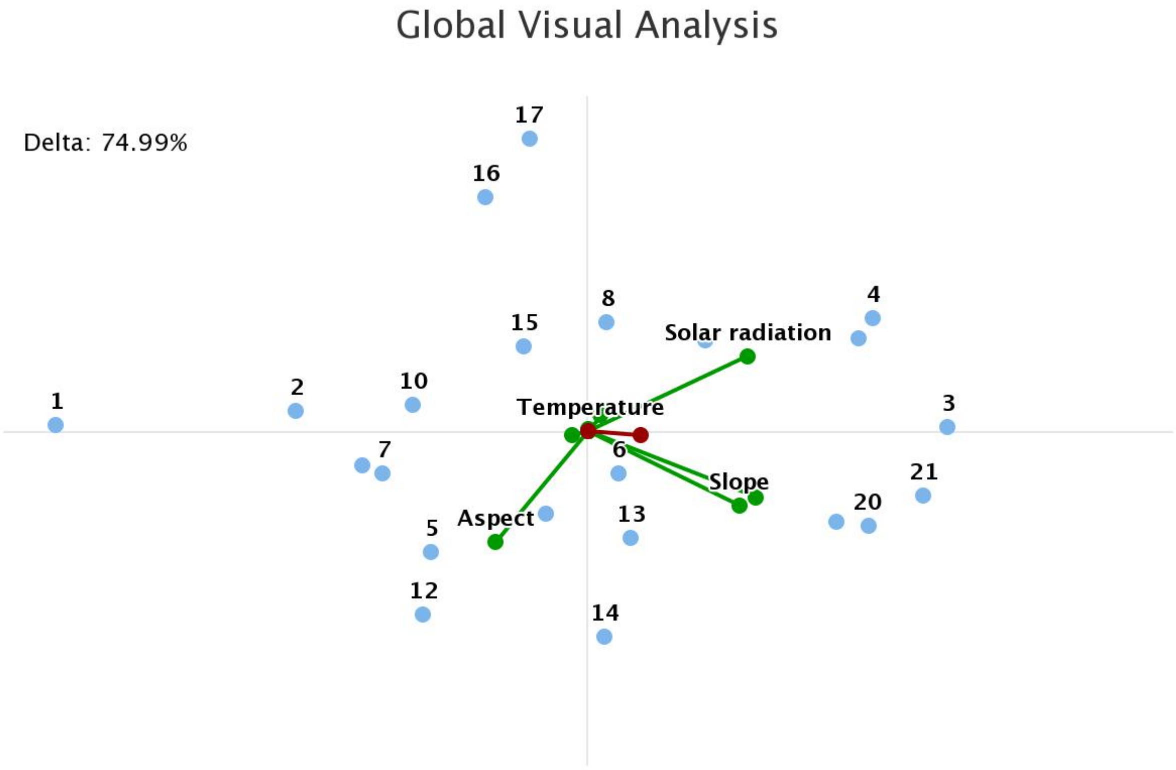


Figure 11: GAIA map/results

Once the ranking is obtained, the resulting data from the multi-criteria evaluation are entered into ArcGis and a map is created (Figure 12). In this way, as well as finding out what the results are in the net flows of each alternative (Figures 10 and 11), the geographical distribution of the areas with the greatest potential for installing solar farms can be observed (Figure 12).

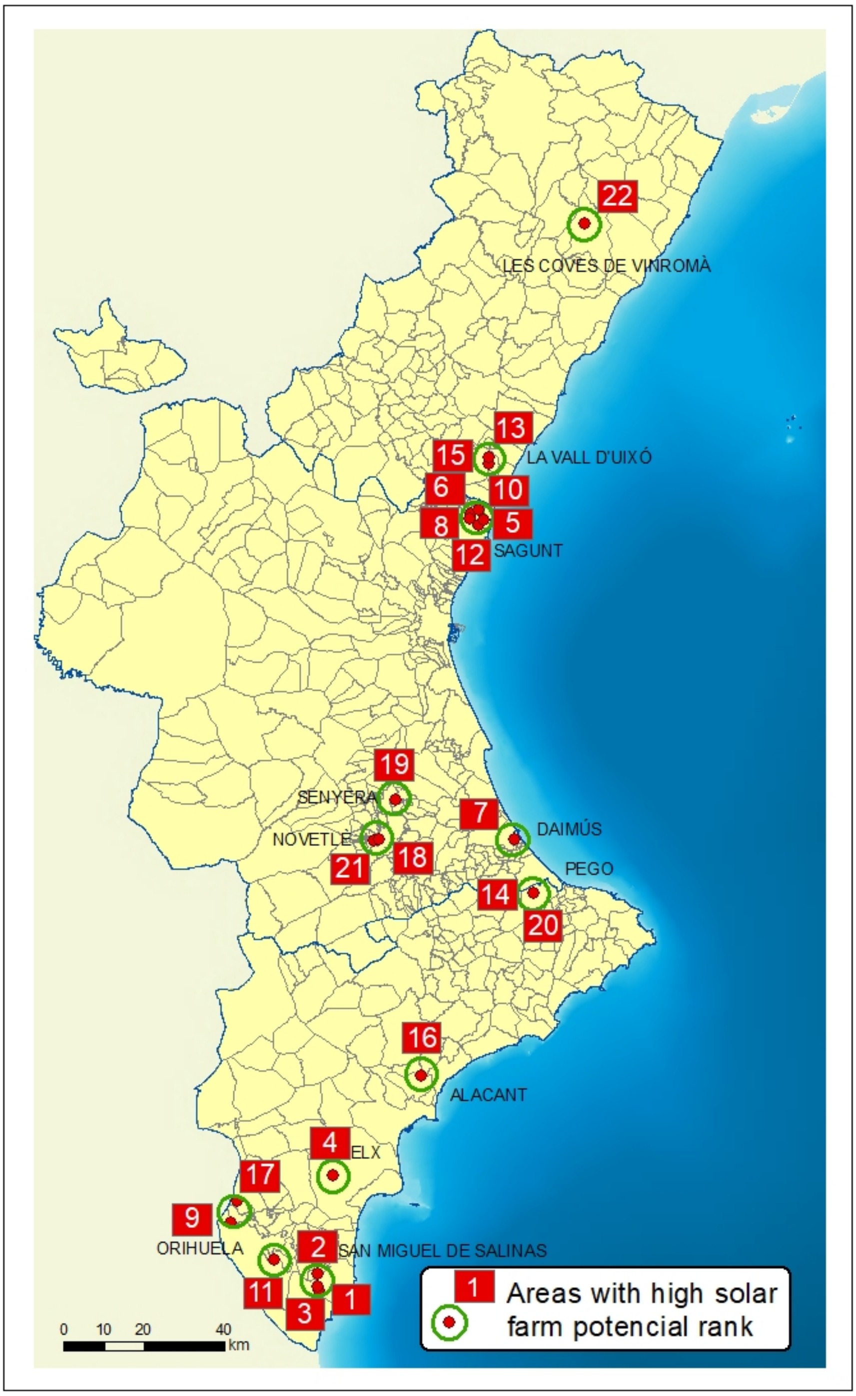


Figure 12. Ranking of areas with high potential for solar farm development

As mentioned above, the locations which obtain a higher aggregate index and are, therefore, the best, are also those with a higher intensity of solar radiation. Furthermore, there appears to be certain parallelism between the technical ranking and the economic performance and viability of the projects. Table 8 shows the financial results for different locations equipped with 400 kWp solar installations and covering an area of 0.8 Ha. The economic profitability of solar farm investments is analyzed using generally-accepted investment criteria , such as the net present value, the internal rate of return, and the payback period (Muñoz et al. 2009) (Kaldellis, Zafirakis, and Kondili 2010) (Tomosk et al. 2017).

Table 8: Energy production and net present value (NPV) for each location

PROMETHEE ranking	Alternative locations	Municipality	Annual PV energy production (KWh)*	NPV (€), without land rental	NPV (€), with land rental	Rates of change for land rentals
1	20	SAN MIGUEL DE SALINAS	684.000,00	854.593,46	450.040,13	1,45%
2	3	LOS MONTESINOS	677.793,57	844.258,17	551.962,00	1,73%
3	4	TORREVIEJA	673.382,97	836.913,39	384.764,11	67,24%
4	9	ELX	670.687,91	832.425,43	418.534,74	-98,48%
5	21	CANET D'EN BERENGUER	655.961,23	807.901,75	263.632,06	13,89%
6	22	SAGUNT	648.694,84	795.801,35	251.531,66	77,92%
7	14	DAIM ┌S	646.787,60	792.625,31	252.041,42	76,60%
8	18	SAGUNT	644.869,84	789.431,75	245.162,06	123,73%
9	8	ORIHUELA	644.192,31	788.303,49	383.750,16	72,88%
10	13	SAGUNT	644.069,84	788.099,55	243.829,85	132,02%
11	15	ORIHUELA	643.912,31	787.837,22	383.283,89	73,72%
12	19	CANET D'EN BERENGUER	643.861,23	787.752,16	243.482,47	177,19%
13	11	LA VALL D'UIXË	643.523,32	787.189,45	197.461,57	-0,01%
14	12	PEGO	638.951,24	779.575,77	227.492,18	88,94%
15	10	LA VALL D'UIXË	638.523,32	778.863,17	189.135,29	116,16%
16	17	ALACANT	637.039,42	776.392,10	351.100,01	119,04%
17	16	ORIHUELA	637.912,31	777.845,69	373.292,36	78,60%
18	5	NOVETLÉ	636.131,98	774.880,98	406.301,06	93,11%
19	6	SENYERA	635.152,89	773.250,55	445.214,41	103,80%
20	7	PEGO	638.951,24	779.575,77	227.492,18	80,64%
21	2	TORRELLA	635.000,00	772.995,95	404.416,02	-212,50%
22	1	LES COVES DE VINROMÁ	622.000,00		530.199,67	1,45%

Source: Elaborated by the author *https://ec.europa.eu/jrc/en/pvgis ** NPV (€) are calculated without payments for land rental

For each location, we know its annual PV energy production (KWh). Cash flows are calculated by taking into account the energy production. The electricity price in Spain is € 0.126 per kWh. The annual variation has been applied according to an estimated inflation of 2.20 %. Payments are allocated to the installation's maintenance and its insurance and are estimated to be 9% according to market criteria. Regarding the NPV, if land rental is not included in the payments, we obtain the same ranking of optimal locations. But if it is included, then, the NPVs obtained are different and may change the ranking. Table 9 shows the difference in the results of the NPV, depending on whether the land rental is considered or not. Moreover, we have calculated the rates of change for land rentals that would make the ranking remain in the same order. For instance, if we consider land rental, option 3, which previously ranked in second place, will have a much higher NPV than option 20, which ranked first. Consequently, the land rental for location 3 should be increased by 1.45%, so that location 1 remains the most interesting option. As may be seen from this example, economic criteria can change the ranking obtained from considering solely technical variables. Therefore, the results of the economic are relevant to the final decision-making process.

4. Conclusion

Bearing in mind today's global concern about the effects of climate change, and that environmental commitments and policies are continuously reviewed and adjusted to new requirements and objectives to be able to face new energy challenges, energy planning is turning into an increasingly complex process where a multiplicity of factors must be taken into account. Thus, contributions including novel approaches are constantly necessary in order to advance in problem solving and to provide new solutions. In our study a new approach is proposed that provides a new method for solving problems related to photovoltaic (PV) spatial planning. The proposed method is based on a GIS (Geographic Information Systems) argumentation map in which areas with high potential for solar farm development are identified. The PROMETHEE and Analytic Hierarchy Process methods are integrated together with GIS in order to obtain a ranking of suitable areas for the development of PV solar farms. The economic analysis of suitable areas is quite relevant since its results are useful for the final decision-making process.

Policy makers can use the proposed method to approach certain aspects of energy policies, such as the territorial planning of energy production activities with solar panels in accordance with the national and European energy policy commitments. The results could also be applied to the promotion of the selected areas for the installation of photovoltaic plants, for example by establishing the facilities to provide financial services and to help make bureaucratic processes easier.

Identifying the best pieces of land for the installation of PV solar farms is highly convenient for several reasons: 1) energy transmission is optimized, 2) a master plan for future solar energy planning can be developed; 3) it provides timely access to selected land; 4) environmentally sensitive lands are identified; and 5) it provides certainty to the solar power market (Gastli & Charabi, 2010).

Moreover, the findings of this study can help governments and investors in PV solar energy planning. The proposed methodology facilitates the development of solar energy production and PV solar farms. It provides governments with an excellent tool for territorial planning, and investors with useful information to estimate a priori the financial results and to be able to develop more and better PV solar projects. In addition, it facilitates the planning of electricity transmission lines which are required to guarantee the technical viability of PV power stations. As a result, governments can make the production of electric power cleaner and more reliable.

This methodology can be applied to any area or region of the world, but with a few exceptions. On the one hand, it is important to consider the environmental, legal, political, and economic criteria that determine the *not excluded areas* specific to each country, and within each country, to each regional department or community with competences in urban and territorial planning, etc. The criteria for the selection of the *areas with high potential for solar farm development* are the same everywhere and possibly have the same weight. However, it is advisable to identify the stakeholders in each country, department, or community and conduct a new survey with them, since they may give different weights to each criterion. Also, economic parameters like initial capital cost, cash flows, discount rates, retail prices, etc., may differ from region to region. On the other hand, the Valencian Community has an important database system which includes relevant geographic information, which allows us to carry out accurate studies and obtain reliable results.

Nevertheless, the study's limitations also need to be considered with the aim of making recommendations and suggesting improvements for future research, mainly regarding the possibility of extending the pool of expertise to other areas of interest and of improving the online survey.

Furthermore, even though there is a wider public acceptance of solar farms compared to wind energy farms (e.g. solar farms have fewer constraints due to visual intrusion or noise, wildlife impacts, etc.), those areas considered as suitable and financially viable should undergo a process of public participation. The society or the population affected can then also decide which are the best locations so as not to destroy high-value landscapes, nor interfere in the creation of job opportunities and rural development. Social preferences regarding certain *social criteria* help to identify the *available geographical areas*. This public participation and decision process could be implemented by means of the AHP methodology which could be the last step in future research studies.

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