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Research Article

Development of a Territorial Planning Model of Wind and Photovoltaic Energy Plants for Self-Consumption as a Low Carbon Strategy

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Energy self-consumption is one of the strategies used for the optimization of renewable energy integration in electrical systems within a framework of sustainable energy policy development. Renewable energy self-consumption additionally contributes to the promotion of distributed generation. The aim of the present study is to develop a hybrid territorial planning model for the siting of areas suitable for the joint exploitation of wind and solar energy targeted principally at self-consumption. The methodology employed was based on the analytic hierarchy process (AHP) and geographical information systems (GIS), and the general area considered was the island of Gran Canaria (Spain). This island has an isolated electrical system. The case study involved locating areas close to populated settlements which are generally cut off from areas commonly marked out for large-scale wind and solar energy exploitation. The areas located with the model were differentiated according to the municipality they were in. The model that has been developed can be applied to any territory. The results obtained with the model can then be incorporated into territorial planning documents and/or national and regional and/or municipal files with the aim of optimizing the integration of renewable energy for self-consumption and advancing distributed electrical energy systems.

1. Introduction

Countries worldwide are becoming increasingly aware of the importance of renewable energy (RE) sources for their energy supply. Directive 2018/2001, on the promotion of the use of energy from renewable sources [1] and within a framework of a low-carbon energy transition (article 3.5 of Directive 2018/2011), established a series of strategic objectives in relation to the contribution of renewables to energy demand. The target set for the European Union (EU) as a whole was for renewable energies to meet 32% of energy demand by 2030. In addition, a series of short-term and 2030-based specific targets were set for the different EU member states (articles 3.4 and 3.2 of Directive 2018/2011). With respect to the particular case of the contribution of REs to meeting the electricity demand in the framework of the EU, Directive 2018/2001 sets out, among others, the following strategic lines:

(a) The large-scale generation of electrical energy from renewable sources is directly connected to the electrical power transmission networks
(b) Energy self-consumption: this strategic line is new in the regulatory framework of the EU

Three distinct figures are considered with respect to the promotion of energy self-consumption: (1) renewables' self-consumer, (2) jointly acting renewables' self-consumers, and (3) renewable energy community (article 2, points 14–16, respectively, of Directive 2018/2001). In this regard, the aim is to promote not only self-consumption by individual or small and medium enterprises (SMEs) but also the joint self-consumption of renewable energy by individuals, SEMs, and/or local bodies, including municipalities.

The participation of renewable energies in the generation of electrical energy as a strategy for a low-carbon energy transition has been the object of study in several recent scientific publications [2–6]. In their studies, Nakazawa et al. [2] and Wang et al. [3] analysed the case of a 100% renewable strategy in residential areas in a transition to low-carbon energy policies. Nikasa et al. [4] developed a methodology for the large-scale integration of photovoltaic solar energy in Greece. These authors considered this to be a key tool for a low-carbon energy transition. Nuwan et al. [5] underlined that a low-carbon economy requires low-carbon consumption on the part of the population. They undertook a study with a sample of the population of Sri Lanka, highlighting the importance of drawing up specific plans and proposing the use of renewable energies as one of the key strategic lines in this respect. Dorotic et al. [6] stressed the major importance of developing energy plans in island electrical systems and territories with limitations in their resources, aimed at achieving energy self-sufficiency and sustainability with zero carbon emissions. They undertook a case study on the island of Korcula (Croatia). To achieve their objectives, they developed a model of the electrical system in which wind and solar energy were incorporated as key elements.

Various authors have also highlighted energy self-consumption with renewable energies as a key tool for low-carbon energy policies [7–9]. Campos et al. [7] stressed the existing link between energy self-consumption and the low-carbon strategy, studying a case with the incorporation of renewable energy sources in a wine-producing industry in the Mediterranean area. In their study, Jimenez-Castillo et al. [8] considered the concept of net zero energy building, highlighting the importance of the incorporation of renewable energy sources and, more specifically, of photovoltaic solar energy for electrical energy generation. For their part, Lopez and Steiningera [9] analysed the regulation of self-consumption with photovoltaic solar energy in Spain, reaching the conclusion, among others, that energy self-consumption plays a key role in the transition to a low-carbon energy system.

In article 15.3, Directive 2018/2001 states that member states must ensure the inclusion of provisions for the integration and deployment of renewable energy at national, regional, and local level, including for renewables' self-consumption and territorial planning necessary for that purpose. Taking into account these requirements, Spain has drafted its own Integrated National Energy and Climate Plan (INECP) 2021–2030 [10]. Among other aspects, strategic targets are set out in the Plan with respect to RE, including a nationwide renewable-sourced energy end use contribution of 42% and a 74% renewable share in electrical energy generation by 2030 (which presently stands at 36.8%).

The INECP of Spain specifically promotes energy self-consumption (see pp. 69–71 in [10]) and, in particular, joint self-consumption through the establishment of local energy communities. In Spain, electrical energy self-consumption is regulated through Royal Decree 244/2019 [11].

In self-consumption energy systems, the points of generation and consumption are relatively close, which thus contributes to distributed generation and the consequent improvement in the quality and cost of the electricity supply. The concept of distributed energy generation (DEG) and its incorporation in electrical system planning has been studied by numerous authors [12–16]. Notably, in all these studies, it is reported that the use of DEG improves the operational quality of electrical systems and is a beneficial strategy in the optimization of RE integration.

Ackermann et al. [12] defined the concept of distributed generation and its importance in electrical systems. In their work, they discussed various aspects that need to be considered for the incorporation of DEG in a competitive electricity market.

Specht and Madlener [15] studied a case for the German electrical system. They concluded that the incorporation of DEG is essential to optimize RE integration in the electrical system. They also considered it interesting to promote RE self-consumption. The same conclusion was reached in a study undertaken by Zhang et al. [16] on the electrical system in China. In their work, an analysis was carried out of the national electrical system, with one of the focuses of the study centred on the importance of DEG at the provincial and municipal level.

Dhakouani et al. [13] applied the so-called Open Source Energy Modeling System (OSeMOSYS) to the electrical system of Tunisia, with the aim of optimizing RE integration. They concluded that, in a framework of sustainability, the proper development of planning initiatives was fundamental for energy transitions. Navon et al. [14] reached similar conclusions in their study on the electrical system of Israel. They studied congestion in the Israeli transmission network as a result of RE integration and proposed the development of long-term planning criteria to promote DEG as a strategy to resolve the problem.

In the work undertaken by Uche-Soria and Rodríguez-Monroy [17] on energy poverty in the Canary Islands (Spain), the authors highlighted six basic pillars which need to be considered for the attainment of energy sustainability, including the exploitation of RE sources, the promotion of energy self-consumption facilities, and the electrification of energy demand. They also underlined the significant potential for RE exploitation in the Canary Islands, particularly solar and wind energy. Finally, they reported on the need for further research to be carried out on the possibility of increasing RE penetration while ensuring the quality of the electricity supply.

With respect to energy self-consumption, Van der Waal [18] carried out a case study on the Scottish island of Shapinsay in the Orkney archipelago, assessing the local impacts of a community self-consumption wind energy project.

The Canary Archipelago (Spain) is a geographical region of Spain which is a considerable distance from the mainland and not connected to the national electrical system. There are 7 main islands in the archipelago, each of which has its own independent electrical system, except for Lanzarote and Fuerteventura which are interconnected. At regional level, the Autonomous Government of the Canary Islands has set a strategic target that RE should contribute 45% to the electrical energy demand of the islands by 2025 [19]. According to the latest data available, the corresponding contribution at the end of December of 2018 was just 11.8% [20].

Gran Canaria is the second most populated island in the archipelago. The island includes zones that are among the world's most prolific in terms of wind and solar energy potential, with mean annual wind speeds (at 10 m above ground level) of over 8 m/s and a solar energy potential which often exceeds 5,000 Wh/m^2/day. Generally, the areas of high wind potential are found near the coast and on occasions at some distance from the island's populated settlements.

The islands in the Canary Archipelago are environmentally fragile territories, and 49.2% of the territory forms part of either the Canary Islands Network for Protected Natural Areas or the EU Nature 2000 network [21, 22].

Wind and solar energy are RE sources which are widely used for the supply of electricity. Their participation in the energy mix of electrical systems is continually rising. Optimizing the integration of RE in electrical systems can be tackled in a number of ways. These include the design of precise models to estimate the RE resource power output [23], the use of optimized smart grids [24] and, very importantly, the development of detailed and precise territorial planning studies for the demarcation of areas of interest for the installation of wind and solar energy facilities. Such studies are particularly important in island territories, where available land tends to be more limited and the electrical systems are generally small and weak. In the demarcation process, the planners need to consider, among many other aspects, the land use in the territory, the access to the areas in question, the potential of the renewable resource, the electrical infrastructure, and the location of areas of energy demand.

Various studies have been published in the literature which propose methodologies to demarcate areas for the installation of wind and/or solar energy infrastructures. These studies concentrate fundamentally on the identification of areas for the large-scale exploitation of these energy sources. In other words, the focus is on the implementation of large-scale facilities whose purpose is to directly dump all the electrical energy they generate into the transmission networks. The areas identified are usually situated in areas with a high renewable resource potential.

In many regions and/or countries, there are populated settlements with considerable energy requirements that are located at some distance from areas commonly demarcated for the implementation of large-scale wind and/or solar infrastructures. It may be possible for RE self-consumption plants to cover the electrical energy demand of these communities, including the demand of municipal facilities and of SEMs established there. However, for this, specific territorial planning has to demarcate areas relatively close to such settlements that have good potential for the joint exploitation of wind and solar energy and where energy self-consumption facilities can be built. Finding appropriate sites for such facilities is a decision-making problem which needs to examine and take into account a wide range of issues. In this regard, multiple-criteria decision-making (MCDM) is a widely used tool in the field of energy planning. Thanks to its flexibility, it allows decision makers to find optimum results in complex scenarios which involve numerous conflicting indicators, targets, and criteria [25, 26]. The application of MCDM requires the support of geographical information systems (GIS), primarily for georeference of the geographical data that are of interest for the study [27, 28]. Various studies have used these tools to identify areas for the large-scale implementation of wind farms [29–35] and photovoltaic solar plants [36–40]. The aims pursued in such studies are generally related to providing assistance in the decision-making processes of governmental institutions. They usually involve assessing the suitability of an area in terms of its energy potential and the economic, social, and environmental impact of any facilities built there. However, all the studies that have been analysed have as their goal the large-scale generation of electrical energy through the direct connection of the wind or photovoltaic facilities with the transmission networks of the existing electrical systems in the study area. No studies have been found in which the specific objective is the siting of areas for the installation of wind or photovoltaic infrastructures aimed at energy self-consumption. At the same time, very few studies have focused on territorial contexts and small insular electrical systems (e.g., [34]). In these cases, it is of fundamental importance to consider factors related to territorial planning because the territory itself is a scarce resource. There are also very few studies which have tackled the joint siting of wind and photovoltaic facilities (e.g., [41, 42]). The most noteworthy study of this type of study was carried out by Aydin et al. [43], who presented a methodology for the siting of hybrid facilities (wind/photovoltaic). This approach favours the optimization of renewable resources in isolated areas because it provides a more stable energy supply by combining both energy sources.

The analytic hierarchy process (AHP) method was found to be the most widely used MCDM technique. In general, the AHP approach weighs the relative importance of each of the set of factors with a view to attaining a specific objective. The most important difference between the different consulted works concerns the criteria adopted for the weighing process. In some of the studies, no explanation is provided as to who assigns the respective weights (e.g. [30, 34]), or the authors themselves assign the weights in accordance with their own experience (e.g., [33]). In some MCDM-based studies, AHP is not used (e.g., [29, 35]), so no weights are applied to the different criteria considered. However, to give practical relevance to the results obtained, the most appropriate action would be to assign weights based on consultations with experts and organizations that know the local context in terms of energy generation and/or planning (e.g., [31, 32, 38, 39, 44]). Another aspect to consider is the sensitivity analysis that is used. In the case of studies related to the siting of wind RE installations, the approach commonly used involves modification of the weights, as site suitability is based on scores for each criterion given by the consulted experts. More specifically, one or a combination of the following techniques is used: (a) an equal weighting is assigned to all the criteria (e.g., [32, 34, 44]), (b) a weighting of zero is assigned to one or more criteria (e.g., [34, 44]), and (c) the weightings of the criteria are modified in a defined interval (e.g., [45, 46]).

The study proposed in the present paper has as its main aim the development of a hybrid model for the siting of territorial areas that are suitable for the joint installation of wind and solar facilities targeted fundamentally at energy self-consumption. For this purpose, the AHP methodology was employed in conjunction with GIS.

The original contributions of this study are as follows:

(a) In the definition of the AHP-GIS model for area demarcation, consideration is given to the fact that the wind and/or photovoltaic installations will be used fundamentally for energy self-consumption. In this way, such systems are promoted as a strategy for the optimization of the contribution of RE sources to meeting energy demand.

(b) The case study focuses on the siting of areas close to populated settlements which are generally some distance from areas commonly demarcated for the large-scale exploitation of wind and solar energy.

(c) The case study is targeted at a limited territory with an isolated and weak electrical system.

(d) The study undertaken in the present paper also includes an original analysis of the sensitivity of the results of the hybrid model to modification of the threshold value in the minimum score criterion. This criterion is taken into account in the fitting stage of the wind and solar models to the hybrid model.

2. Data and Methodology

2.1. Study Area. The study area is the island of Gran Canaria, part of the Canary Islands Archipelago (Spain) (see Figure 1). This archipelago is found off the northwest coast of Africa between latitudes 27°37′ and 29°25′ N and longitudes 13°20′ and 18º10′ W. The surface area of Gran Canaria is 1,560 km^2 and its population is 846,717 [47]. Mean solar radiation is approximately 1,900 kWh/m^2/year and mean wind speed is 6.4 m/s at a height of 40 m above ground level (see Data Availability). At the end of 2018, the island's installed wind and photovoltaic capacities were 154.3 and 41.5 MW, respectively. This is equivalent to 100% of the total installed renewable power on the island. Total installed electrical power was 1,219.9 MW. RE-sourced electricity generation on the island corresponds to a weight of 11.8% in the island's electrical energy demand [20].

Of the total installed wind capacity, only 20.8 MW is self-consumption installation. In the case of solar capacity, the proportion of installations for self-consumption is minimal.

2.2. Methodological Framework. Finding suitable sites for the installation of wind and PV plants, targeted principally at energy self-consumption and the promotion of DEG, is a decision-making problem which requires consideration of different criteria. Normally, a combination of MCDM and GIS is used to analyse and resolve the problem [27, 28, 39]. Pohekar and Ramachandran [48] carried out a review of GIS-MCDM methods and concluded that AHP was the most extensively used technique in RE studies. AHP is an MCDM approach which is based on decomposing, comparative judging, and synthesising the priorities of the decision problem [49]. According to the literature related to the identification of areas for the exploitation of wind and solar energy, an AHP is used because of its flexibility in combining qualitative and quantitative criteria [50] because it allows clear identification of the relative importance of each criterion [51]. In addition, it is intuitive and easy to implement in a GIS.

The suitability analyses of wind and solar installations were carried out separately (see Figure 2). The process began with a review of the literature related to the siting of each energy type in order to select the criteria that need to be considered. These criteria were classified into factors, which favour or condition the location and constraints, which limit the location.

2.2.1. Identification of Factors. Nine factors used to identify the most suitable sites were found in the review of the literature. Each factor (Table 1, and see Data Availability for sources) was standardised through a linear membership function considering the critical points shown in Table 1.

Consideration was given to wind speed and solar radiation as factors related to the renewable resource potential. Wind speed is the key factor for wind energy exploitation [30–32, 34, 35, 44, 45]. In this study, the areas considered most suitable for exploitation were those with mean annual wind speeds above 7 m/s, while those below 4 m/s were discarded. For its part, solar radiation is the key variable for the generation of photovoltaic energy [36–38, 42, 43]. Based on the references that were consulted, although solar radiation was above 4,000 Wh/m^2/day in all the selected areas, those considered most suitable enjoyed over 5,000 Wh/m^2/day.

With respect to environmental criteria, factors such as visual impact, slope, and slope direction were considered. The first of these is related to wind energy [30, 32, 34, 44, 52]. Bearing in mind the importance of the tourist sector in Gran Canaria, consideration was also given to the visual impact that wind turbines could have on the historical points of interest of the island. The criterion to evaluate this factor was that areas with a visual impact on more than 4 points of interest would not be considered suitable, while areas not visible from any point of interest would be considered the most suitable. In this case, the ArcGIS Viewshed Analysis was used to determine the degree of visibility, considering the observation points (historical sets) to be at a person's eye level (1.7 m.) and a 40 m tall wind turbine in each of the digital elevation model (DEM) cells. It was also considered that areas with steep slopes (greater than 30%) were unfeasible locations for the construction of wind farms [30–32, 34] or PV plants [36, 38, 43], as access for construction would be extremely difficult and have a major

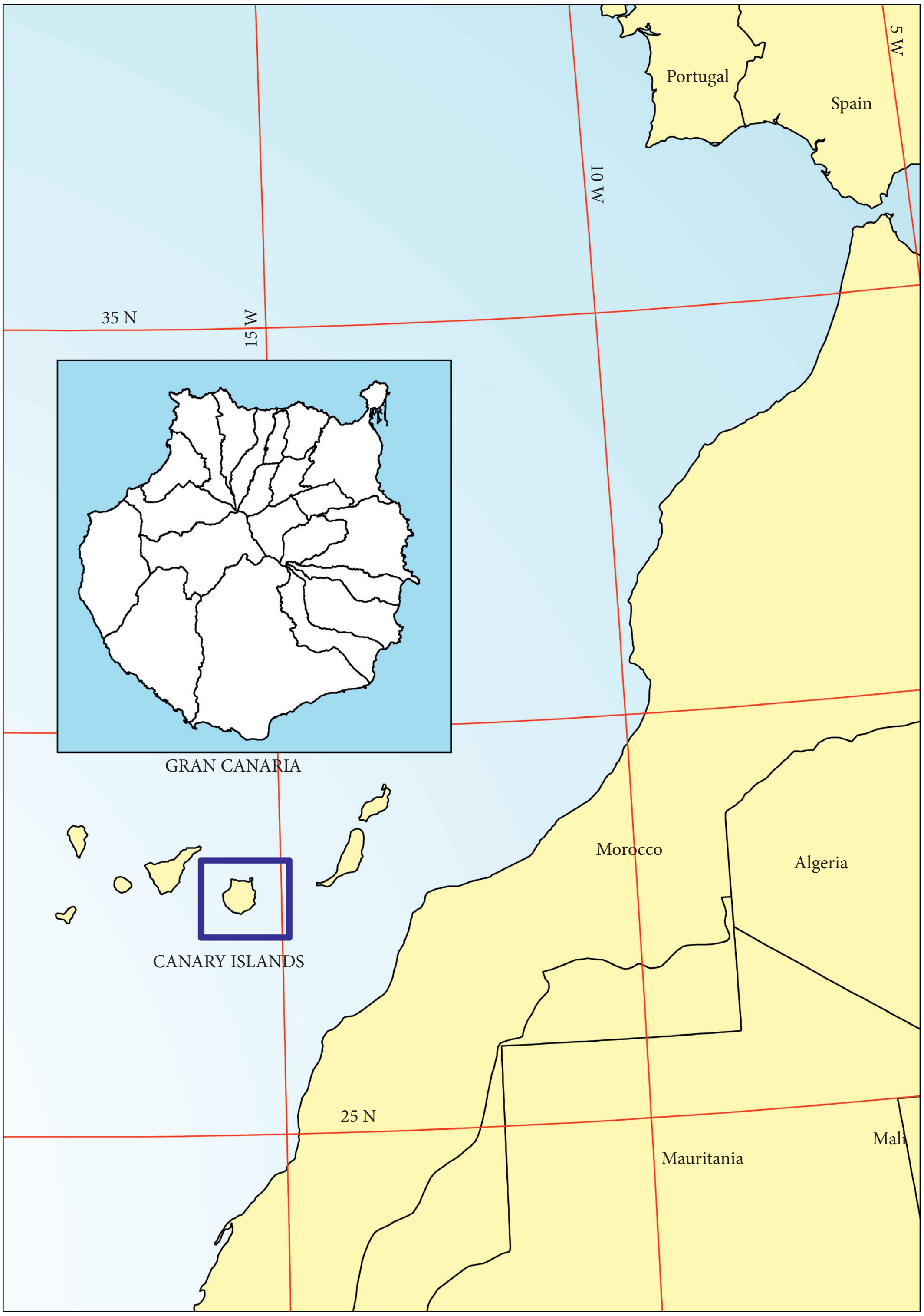


Figure 1: Geographical location of Gran Canaria island.

economic and environmental impact. In this case, it was considered that areas with a slope below 10% were the most suitable for wind farms. The constraint for solar plants was greater, with a 3% limit, as the infrastructure required to install solar panels requires a large surface area and the earthworks to condition the land which could generate significant shaded areas. Finally, slope direction was additionally considered with respect to solar installations [36–38, 44]. It was determined that south-facing areas would have a considerably larger solar resource than north-facing areas. In this case, different critical points were established: one section between 337.5° and 22.5°, with a degree of

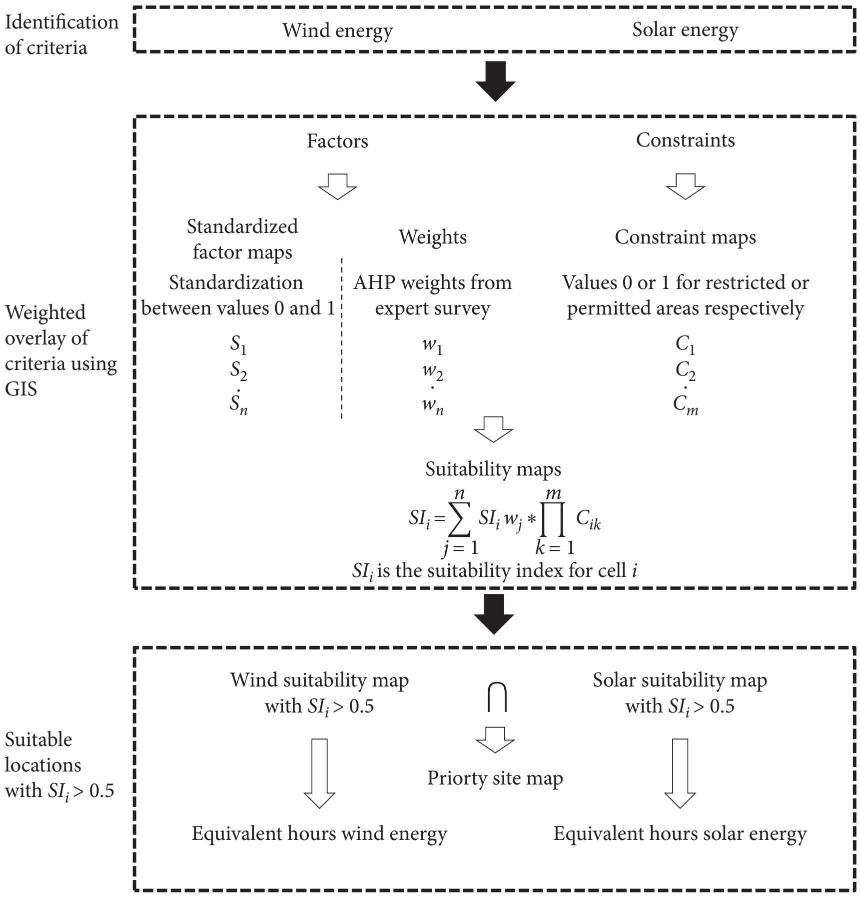


Figure 2: Methodological framework.

Table 1: Classification of factors.

Type of criterion		Factors	Critical points
Energy potential	F1	Wind speed (*)	Less than 4 m/s = 0 More than 7 m/s = 1
	F2	Solar radiation (**)	Less than 4,000 Wh/m^2/day = 0 More than 5,000 Wh/m^2/day = 1
Environmental	F3	Visual impact (*)	Visible from more than 4 places of interest = 0 Visible from 0 places of interest = 1
	F4	Slope	Less than 10% = 1(wind) Less than 3% = 1 (solar) More than 30% = 0
	F5	Slope directions (**)	Between 337.5° and 22.5° = 0 Between 157.5° and 202.5° = 1
Economic	F6	Territorial planning	Incompatibility with IDP = 0 Compatibility with IDP = 1
	F7	Proximity to road access	More than 2,000 m = 0 Less than 200 m = 1
	F8	Proximity to the potential electricity self-consumption	More than 2,000 m = 0 Less than 200 m = 1
	F9	Demand	More than 500 inhabitants = 1 Less than 100 inhabitants = 0

(*) is only for wind suitability maps. (**) is only for solar suitability maps.

suitability of 0, and a second section between 157.5° and 202.5°, with a degree of suitability of 1.

A total of four factors were considered in relation to the economic criterion: territorial planning, proximity to roads, proximity to the self-consumer, and potential volume of energy demand. With respect to territorial planning, land organization and use in Gran Canaria is based on the Island Development Plan (IDP) [47]. In addition, each municipality on the island has its own development plan which is dependent on the IDP. The ultimate aim of these plans is to guarantee sustainable development on the island. The IDP incorporates the coordination of supramunicipal actions and reflects the direction that the authorities are taking in terms of public investment policies. Land classification in the IDP is based on differentiation between the following groups or categories: Zones A (land of high natural value), Zones B (areas where natural values of importance coexist with traditional production activities), Zones C (land used for infrastructures and services of importance for the island), and Zones D (urban or developable land). Each of these groups is further divided into subcategories. After analysing the IDP, the areas that were considered most compatible for the installation of wind and solar plants for energy self-consumption were the following: Ba3 (low natural value and scarce productive value), Bb1.1 (potential productive value), Bb3 (moderate agricultural value), Bb4 (abandoned rural land), C (infrastructures, facilities, and installations of island-wide interest), and D1 (developable industrial land). The availability of a road network close to the potential wind farm and solar plant sites was also considered advantageous as it would reduce the construction costs of new access roads [30–32, 34, 44, 53]. In this study, roads with a minimum width of 4 m were considered. As the study area is an island of very uneven orography, the distance to any communication road was considered in terms of a maximum value ranging between 200 m and 2,000 m. The proximity of these types of installations to populated settlements also enhances their feasibility due to lower cabling costs and energy transmission losses. In the literature, this criterion is usually associated with proximity to the distribution grid [30, 32, 34, 36, 38, 44]. The ideal distance was determined to be between 200 m and 2,000 m. Finally, areas with a higher population evidently require more energy than less populated areas [34, 36, 42, 45], so the demand for self-consumption installations increases, as does their feasibility. Bearing in mind the demographic characteristics of the territory in question, it was estimated that population concentrations of more than 500 inhabitants would be the most suitable, while populations below 100 would not be sufficiently attractive for the installation of this type of infrastructure.

2.2.2. Identification of Constraints.

Based on a review of the literature and the regulations applicable to the study area, the constraints shown in Table 2 were considered (see Data Availability):

(i) The location of wind farms and solar plants must not conflict with territorial biodiversity conservation policies. These exclusion zones include the Canary Islands Network for Protected Natural Areas and the EU Nature 2000 network.

(ii) These types of infrastructure cannot be installed on water-covered surfaces and, therefore, elements such as lagoons, lakes, marshland, dams, or reservoirs were discounted.

(iii) The Canary Islands Road Regulation Act [54] was taken into account, especially in relation to article 45 which sets out the recognised minimum distances from public domains.

(iv) For the case of wind energy, the Autonomous Government of the Canary Islands stipulates in article 29.2 of Decree 6/2015 that the distance between a wind turbine and an inhabited area must be no less than 250 m for turbines with a unit power of less than 900 kW. The aim is to minimize the possibility of acoustic pollution. This was taken as the constraint distance for this study given that the power range of wind turbines that would be installed with respect to the purposes of the present study would be below 900 kW. With respect to solar energy, consideration was given to the perimeter of urban areas which would make the implementation of this type of installation impossible.

(v) In Royal Decree 1471/1989 on coastal regulations, article 43 establishes a sea-land construction limit that extends 100 m inland from the shoreline.

(vi) In Framework Law 5/2005, article 30 establishes limitations for the construction of civil installations in designated military zones.

(vii) A safety area needs to be established with respect to airports to limit air space and ensure the required area is free of obstacles. The approach and departure areas were taken into consideration in this regard for the present study.

(viii) The Special Territorial Plan for Infrastructure Development (PTE-32) of Gran Canaria allocates three specific zones for large-scale RE exploitation. These three zones were excluded. In any case, the aim of the present study is not concerned with large-scale electricity generation, but rather the generation of electrical energy for self-consumption targeted, in general, at meeting the electrical energy demands of municipal facilities and agricultural, livestock, tourist and small industrial activities, etc., in rural areas.

(ix) With a view to avoiding an excessive number of scattered RE installations constructed on small plots which could have an excessive visual impact, the constraint imposed on plot size was that there must be sufficient space for solar energy

Table 2: Constraints.

Constraints	Constraint area
Protected areas Canary network of protected natural spaces Special areas of conservation Areas of special protection for birds (wind only)	The perimeter of protected areas
Water bodies	The perimeter of reservoirs
Roads	20 m from the centre axis Acoustic pollution >250 m urban area (wind only)
Urban area	The perimeter of the urban area (solar only)
Sea-land limits	100 m inland from the shore
Military areas	The perimeter of military areas
Airports	Approach and departure areas
Special territorial plan-32 (STP-32)	The perimeter of designated areas
Minimum surface area	Plots with surface area >30,000 m^2

installations of over 2.5 MWp (30,000 m^2). According to technical specialists, an area of 12 m^2 is required to install 1 kWp.

2.2.3. The AHP Method. The relative importance of each factor was evaluated by a group of experts. These were selected to reflect different approaches and interests related to energy planning and/or the implementation of RE installations. In this respect, assessments were received from the following institutional bodies and enterprises:

(i) The Technological Institute of the Canary Islands (Spanish initials: ITC): this R & D enterprise is managed by the Autonomous Government of the Canary Islands and specialises in RE technologies and sustainable development [55].

(ii) Gran Canaria Island Energy Board, responsible for, among other questions, the design of the energy model for the ultimate goal of the island's energy sovereignty [56].

(iii) The Consortium of Municipalities of the southeast of Gran Canaria: this Consortium represents 3 of the 21 municipalities of the island. This Consortium has a particular interest in territorial sustainability, for which it has been given three awards: 3rd prize in the Whole City category of the international Livcom Awards, Chicago USA (2010), the Eolo prize for the rural integration of wind energy, awarded by the Wind Enterprise Association of Spain (2012 and 2018), and the National Sustainable City Award (2008 and 2010) [57].

The factors considered were compared pairwise, one by one and on a scale of 1 to 9. For this comparison, a matrix was used in which the relative importance of each criterion was calculated as the normalised geometric mean of each row of the matrix. Subsequently, the consistency of the result obtained was measured using the consistency index (CI):

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

where $\lambda_{\max}$ is the largest eigenvalue and n is the number of criteria considered.

Finally, an estimation was made of the coherence of the comparisons using the consistency ratio:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{2}$$

where CR and RI are the consistency ratio and the random index (average CI of the randomly generated comparisons [58]), respectively. The CR must be below 0.1 for the result to be considered acceptable [59].

Tables 3 and 4 show the value of the weights for each of the factors obtained on the basis of the criterion of relative importance as evaluated by the consulted experts.

As determined by the experts consulted, wind speed and solar radiation were the most important factors, with final respective weights of 41.08% and 39.97%. Demand and proximity to potential RE self-consumption sites were classified at a second level, with these factors more closely related to the economic viability of the project. The CR in the case of wind energy was 8.5% and in the case of solar energy was 7.8%, values which are below the threshold value of 10%.

As each factor is expressed in different measurement units, it was necessary to standardise these variables in order to facilitate their joint analysis. Standardisation of the factors was carried out using a linear membership function [43, 45], considering the critical points shown in Table 1. Each constraint was classified with a Boolean criterion, where 0 represents the presence of a constraint and, therefore, the area in question is not feasible, and 1 represents the absence of a constraint and is, therefore, potentially feasible.

2.2.4. Suitability Maps. The wind and solar energy suitability maps were obtained multiplying each standardised factor by its weight. In these maps, the most suitable areas will have a score approaching 1 and the least suitable a score approaching zero. The implementation and visualization of the results was performed with ArcGIS 10.6.

One of the main drawbacks of the use of RE is its dependence on meteorological and climate conditions, and its consequent intermittent nature. It is therefore difficult to

Table 3: Pairwise comparison matrix and relative importance weights of the factors associated with wind energy.

	F1	F3	F4	F6	F7	F8	F9	Weights
F1	1	9	8	6	7	4	3	0.4108
F3		1	1/2	1/5	1/3	1/6	1/8	0.0252
F4			1	1/3	1/2	1/5	1/6	0.0373
F6				1	2	1/3	1/4	0.0857
F7					1	1/4	1/5	0.0553
F8						1	1/2	0.1589
F9							1	0.2268

$\lambda_{\max} = 7.675$; CI = 0.113; RI = 1.32; CR = 0.085 < 0.1.

Table 4: Pairwise comparison matrix and relative importance weights of the factors associated with solar energy.

	F2	F4	F5	F6	F7	F8	F9	Weights
F2	1	9	6	5	7	4	3	0.3997
F4		1	1/3	1/4	1/2	1/6	1/8	0.0262
F5			1	1/2	3	1/3	1/6	0.0652
F6				1	4	1/2	1/3	0.0976
F7					1	1/5	1/6	0.0369
F8						1	1/2	0.1480
F9							1	0.2264

$\lambda_{\max} = 7.615$; CI = 0.103; RI = 1.32; CR = 0.078 < 0.1.

provide a stable energy supply if using only one RE source. However, combining two or more RE sources in a hybrid system helps to overcome this limitation as, when production from one resource decreases, it may be possible for the other resource to compensate for this decrease. Bearing in mind the aim of the present study and taking [43] as reference, it was decided to prioritise the selection of areas in which the installation of both wind and solar energy (hybrid model) was permitted. This entails considering the factors and constraints which affect both energy sources simultaneously. In this study, the criterion was used for choosing priority areas which were allowed to have both types of installation which have values above 0.5 in the suitability analysis of the two energy sources.

2.2.5. Wind and Solar Equivalent Hours. The equivalent hours' parameter was used to provide an overview of the energy potential, both wind and solar, of the areas obtained as results of the hybrid model. This parameter reflects the equivalent annual specific energy generated in a particular area by a wind installation (in kWh/kW) or solar installation. The latter is expressed in $\mathrm{kWh/kW_p}$, where $\mathrm{kW_p}$ is the power measured on the basis of the power specified for the photovoltaic modules.

A tool developed by the ITC was used for the calculation of equivalent hours (see Data Availability for sources of factor: "wind speed"). One of the applications of this tool contains information about the wind resource parameters required to estimate the Weibull function [60] in any point of the Canary territory in a 10×100 m mesh. Based on this information and in combination with another of the tool's applications which makes use of wind turbine power curves, it was possible to estimate electrical energy generation.

For the particular case of equivalent solar hours, direct use was made of data accessible through the web portal developed by GRAFCAN (see Data Availability for sources of factor: "Solar radiation").

2.2.6. Sensitivity Analysis. After the above described process was concluded, it was necessary to carry out a what-if sensitivity analysis to provide information about the robustness of the results [61]. In the case of studies related to the siting of wind RE installations, the approach commonly used involves modification of the weights, as site suitability is based on scores for each criterion given by the consulted experts. More specifically, one or a combination of the following techniques is used: (a) an equal weighting is assigned to all the criteria (e.g., [32, 34, 44]), (b) a weighting of zero is assigned to one or more criteria (e.g., [34, 44]), and (c) the weightings of the criteria are modified in a defined interval (e.g., [45, 46]).

In the present study, it was decided to undertake the sensitivity analysis by considering two different approaches:

(a) According to the criterion of weights assigned to the factors of the model: in this case, the results obtained with the expert-assigned weights were compared with the results obtained on the basis of the criterion of equal weighting for each factor. This allowed evaluation of the impact of the relative importance assigned to each factor.

(b) According to the criterion of assigning a minimum suitability score in the hybrid model: the aim behind this second analysis was to evaluate the sensitivity of the final area available according to the different minimum scores assigned to the hybrid model.

Both analyses were undertaken considering the additional importance, for the case study, of surface area optimization due to land limitations in an island environment.

3. Results and Discussion

3.1. Wind and Solar Suitability Maps. The wind and solar evaluation maps were obtained (see Figures 3 and 4) by overlaying the factors corresponding to wind and solar energy shown in Table 1 (see factor maps in figure 5) and applying the weights according to the pairwise comparison matrices (Tables 3 and 4). In the case of wind energy (see Figure 3), the most suitable areas were the NW, E, and SE of the island. These areas have high wind speeds and are close to important population centres and road networks. In addition, the E area is one of low slope terrain. In the case of solar energy (see Figure 4), it can be estimated that 68% of the island has a score above 0.8 and only 31% has a score below 0.5. These high scores are due to the fact that 79% of the surface area of the island has solar radiation values above 5,000 $\mathrm{Wh/m^2/day}$ because there is a homogenous distribution of populated settlements which favourably affects the

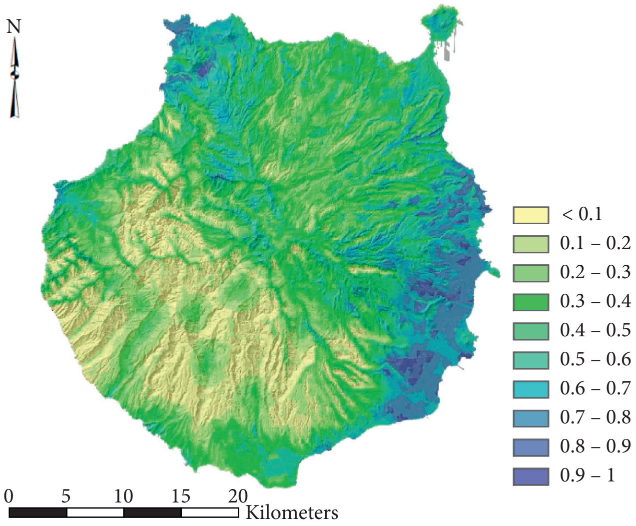


Figure 3: Wind evaluation map.

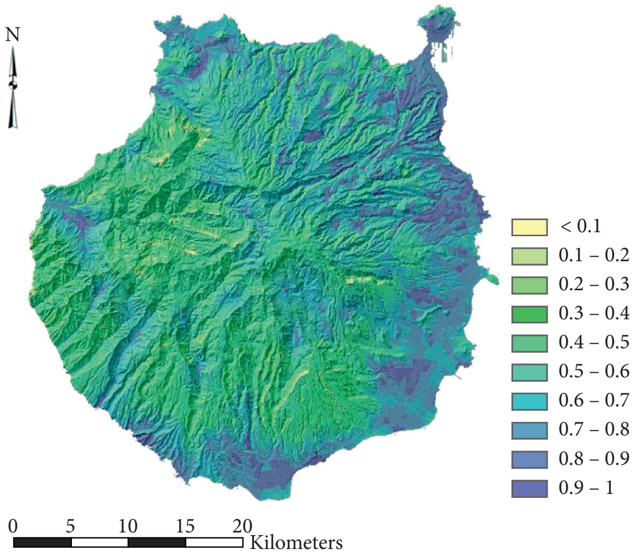
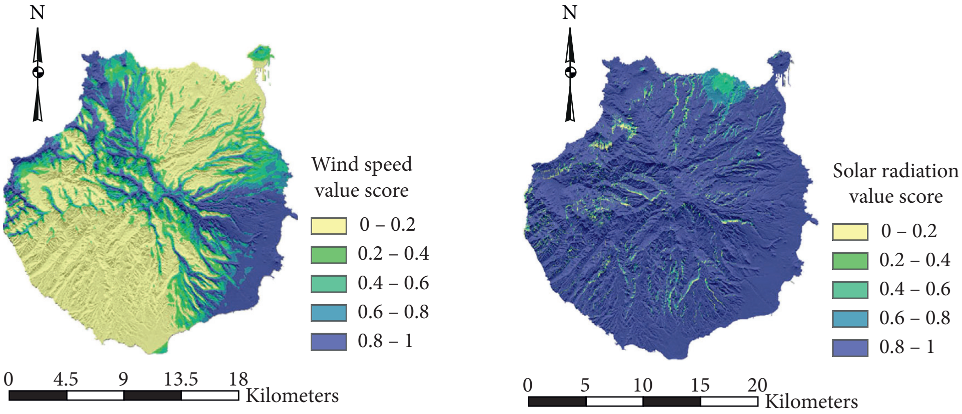


Figure 4: Solar evaluation map.



(a) (b)

Figure 5: Continued.

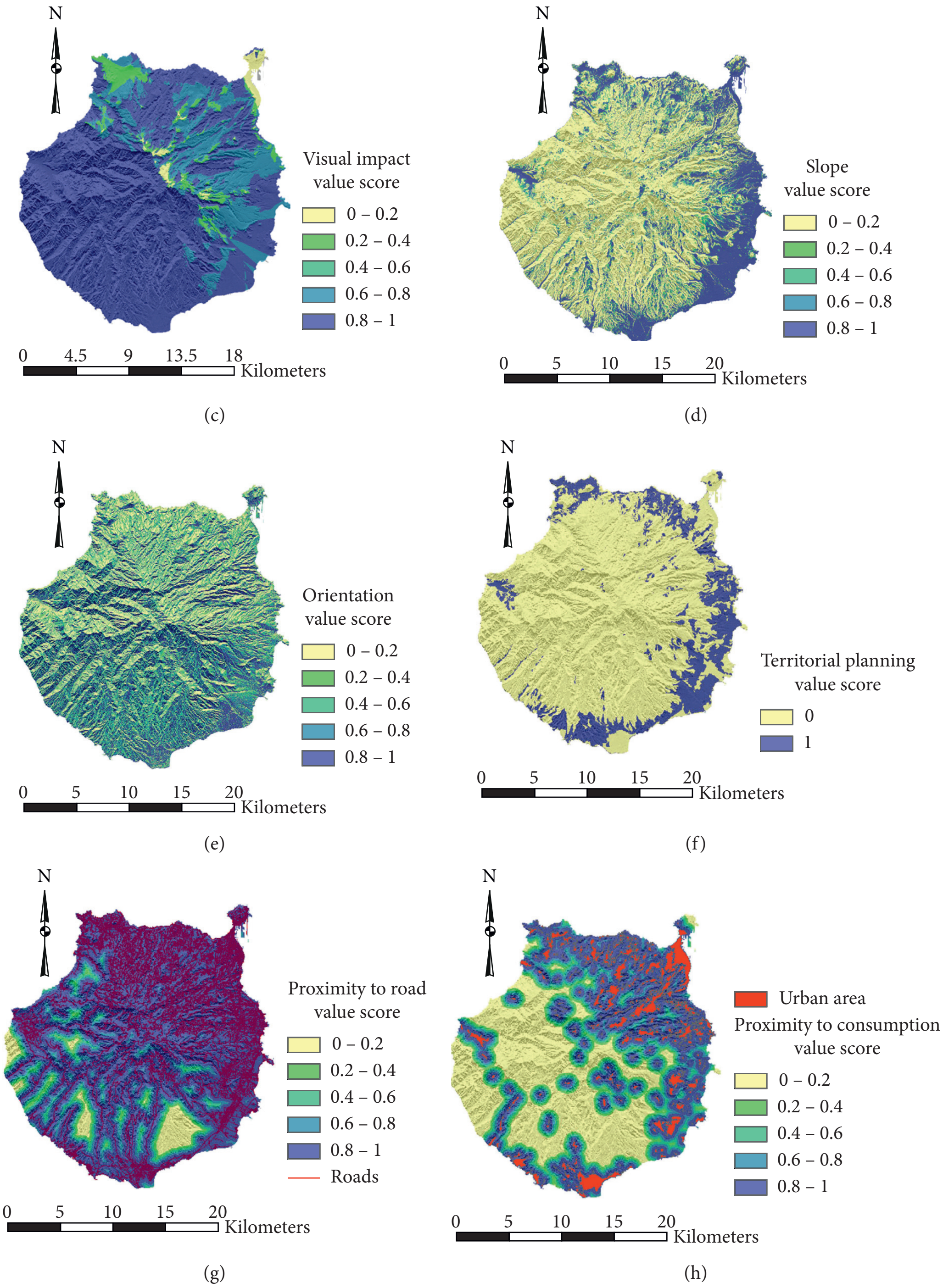
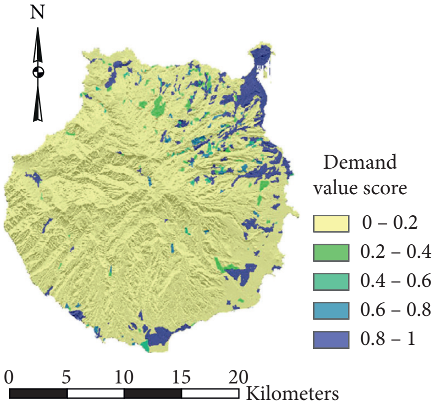


FIGURE 5: Continued.



(i)

Figure 5: Factors: (a) wind speed, (b) solar radiation, (c) visual impact, (d) slope, (e) orientation, (f) territorial planning, (g) proximity to road access, (h) proximity to potential electricity self-consumption, and (i) demand.

scores in the factors of demand and proximity to potential self-consumption.

The wind and solar constraint maps were obtained (see Figures 6 and 7) taking into consideration the constraints corresponding to wind and solar energy shown in Table 2 (see constraint maps in figure 8). In this case, available surface areas of 282.34 km^2 and 388.91 km^2 were obtained for wind and solar energy, respectively. These areas represent 18.1% and 24.9% of the total surface area of the island, respectively.

The wind and solar suitability maps were finally obtained (see Figures 9 and 10) after eliminating the restricted areas from the respective evaluation maps. In the case of wind energy, 81% of the suitable area has a score below 0.5, 18% has a score of between 0.5 and 0.8, and only 1% has a score of above 0.8. In the case of solar energy, only 16.7% has a score below 0.5, the majority (80%) of the suitable area has a score between 0.5 and 0.8, and 3.3% has a score above 0.8. That is, in general, the score for available terrain in the case of wind energy is mostly low, whereas solar energy is characterised by a medium suitability. However, it is important to take into account the fact that the aim of the present study is concerned with DEG in areas distant from large-scale RE infrastructures connected to the transmission network. With this in mind, the STP-32 areas, which are the areas most favourable for the large-scale exploitation of wind energy on the island and therefore reserved for this purpose, were excluded.

3.2. Priority Sitemap (Hybrid Model). As previously indicated, one of the drawbacks of using only one RE modality (wind or solar) is that neither type generates energy continuously, as they are dependent on meteorological factors. The integration of both types of technology in a hybrid system favours the continuity of energy production as they can complement each other. However, the suitable areas with respect to each RE type do not necessarily overlap, as they depend on different factors and constraints (see Figures 9 and 10). It was therefore necessary to carry out a selection of the most suitable common areas (priority areas). The criterion used was the simultaneous occurrence of values above 0.5 for both energy sources [43]. The result obtained is shown in Figure 11.

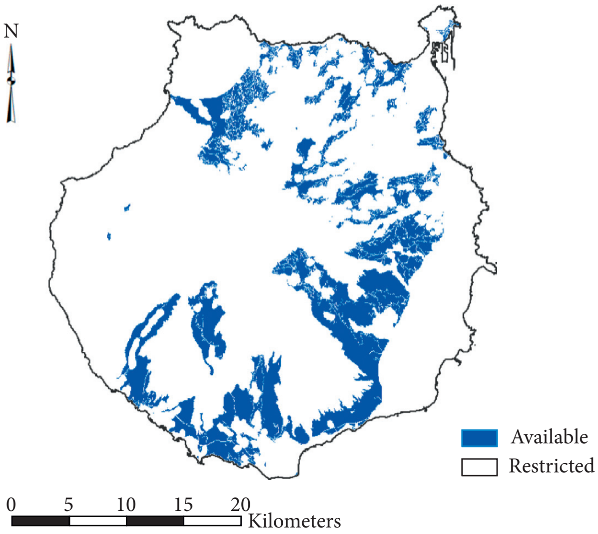


Figure 6: Wind constraint map.

In addition, the location of each of these areas was determined by municipality, as such information could be extremely useful for local administrations in the elaboration of strategic plans at municipal scale. A total available priority surface area of 45.26 km^2 was obtained. The distribution of this area by municipality is shown in Table 5.

3.3. Maps of Equivalent Solar and Wind Hours. Figures 12 and 13 show the annual distribution of equivalent hours (EH) of the areas with a score above 0.5 for wind and solar energy, respectively. These results were obtained on the basis of Figures 9 and 10 and after eliminating the areas with a score below 0.5. In both maps, the areas which form part of the priority area (wind > 0.5 ∩ solar > 0.5, see Figure 11) are enclosed by a red line. According to Figure 12, with respect

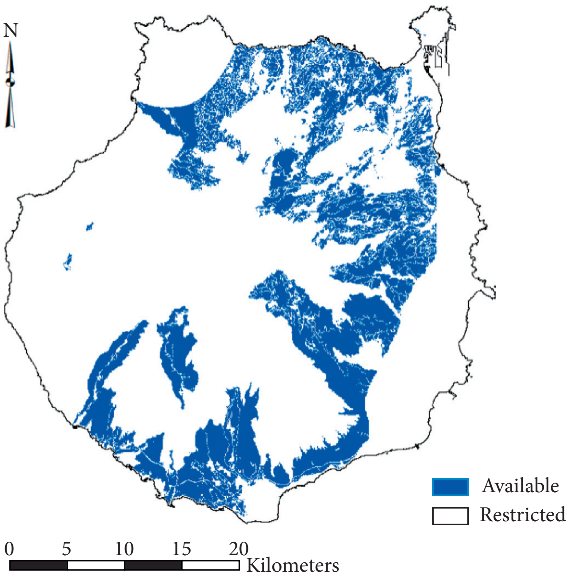
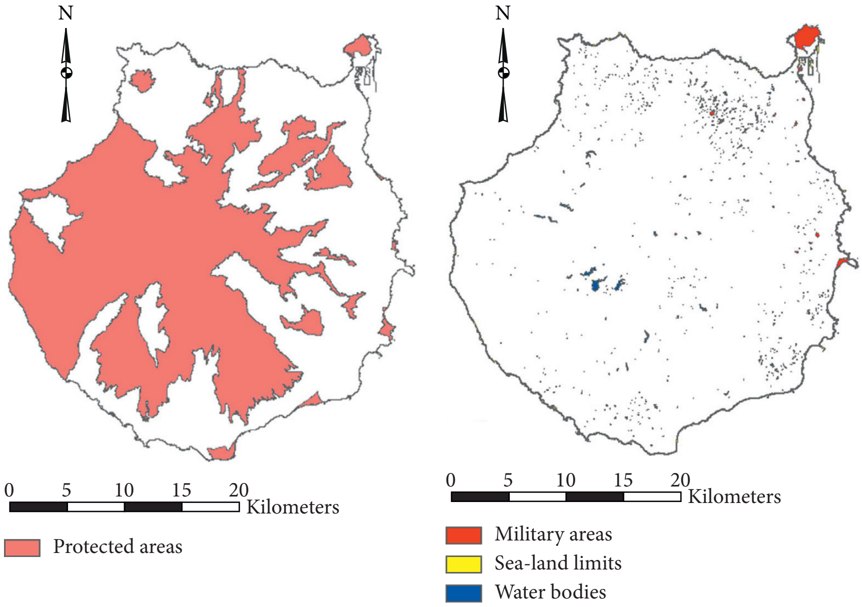


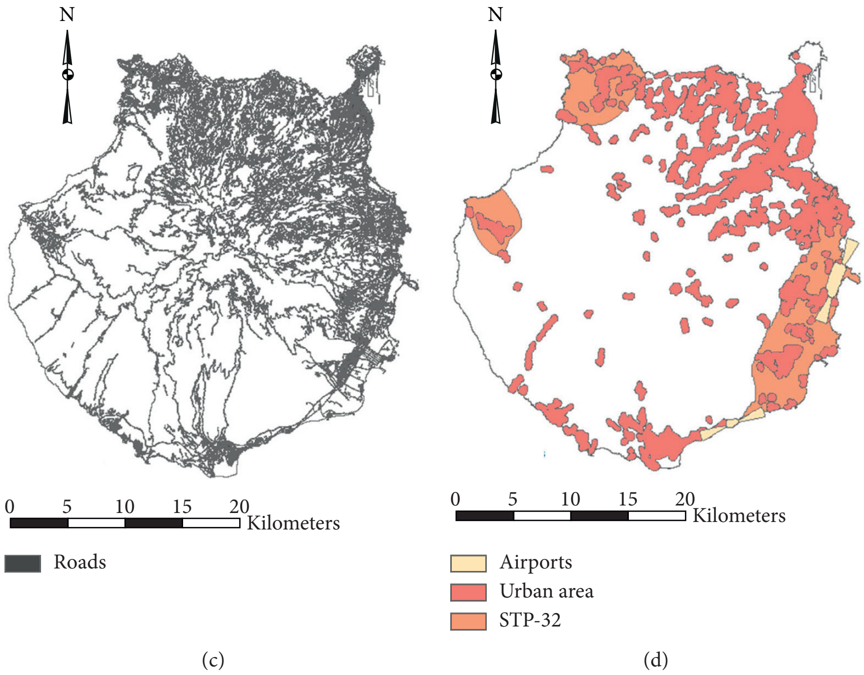
Figure 7: Solar constraint map.



(a)

(b)

Figure 8: Continued.



(c) (d)

Figure 8: Constraints: (a) protected areas, (b) military areas, sea-land limits (100 m), and water bodies, (c) roads (20 m), and (d) airports, urban area (250 m), and special territorial plan-32.

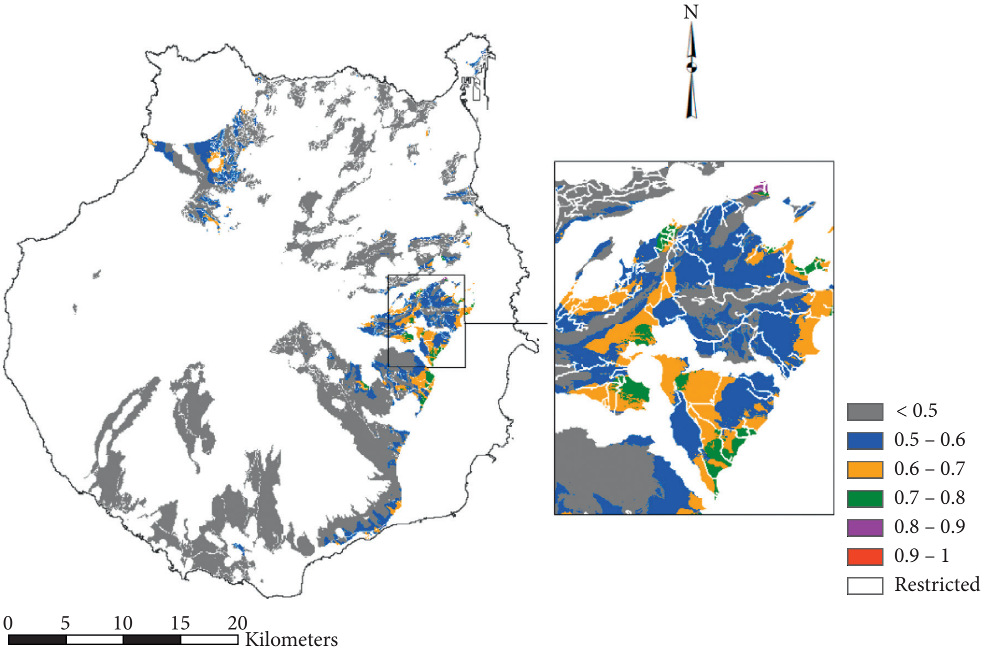


Figure 9: Wind suitability map.

to territorial distribution, 6% (2.9 km^2) has less than 2,000 EH, 43.3% (21.4 km^2) between 2,000 and 3,000 EH, 47.9% (23.6 km^2) between 3,000 and 4,000 EH and 2.8% (1.4 km^2) more than 4,000 EH.

In the case of solar energy, 14.5% of the total area (see Figure 10) forms part of the priority areas in the hybrid model. According to Figure 13, with respect to territorial distribution, 12.3% (38.4 km^2) has less than 1,800 EH, 26.4%

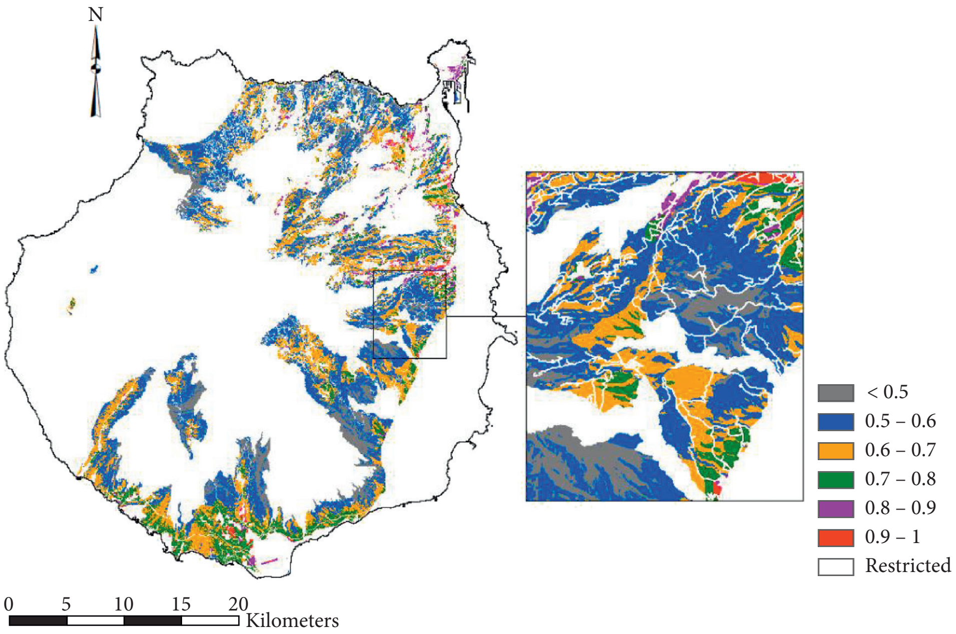


FIGURE 10: Solar suitability map.

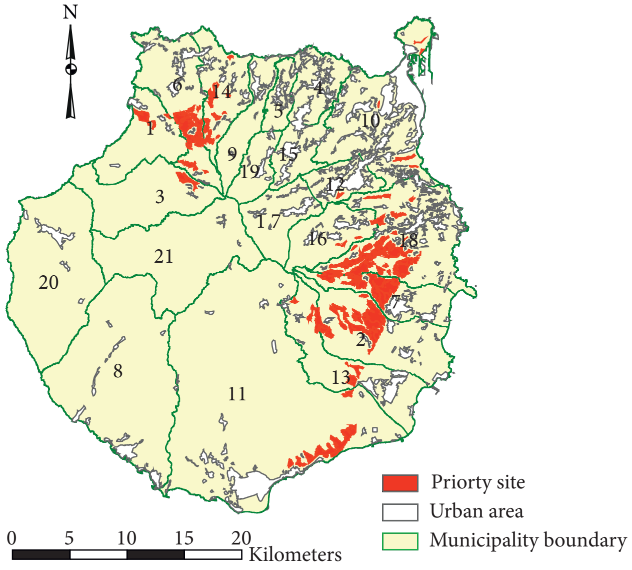


FIGURE 11: Priority sitemap (hybrid model).

TABLE 5: Distribution of available priority surface area by municipality.

Municipality	No.	Surface area (km^2)
Agaete	1	1.36
Agüimes	2	8.88
Artenara	3	0.94
Gáldar	6	5.21
Ingenio	7	7.50
Las Palmas de G. C.	10	0.57
San Bartolomé de Tirajana	11	4.97
Santa Brígida	12	0.11
Santa Lucía de Tirajana	13	2.10
Santa María de Guía de G.C.	14	2.00
Telde	18	11.33
Valsequillo de G.C.	19	0.29
TOTAL		45.26

(82.4 km^2) between 1,800 and 1,900 EH, 51.4% (160 km^2) between 1,900 and 2,000 EH, and 9.9% (30.7 km^2) more than 2,000 EH.

3.4. Sensitivity Analysis

3.4.1. Sensitivity to the Expert-Assigned Weight Criterion. For this approach, the results obtained according to the expert-assigned weight criterion (see Figures 10 and 11) were compared with those obtained with the criterion of equal weights for each factor [32]. For this latter criterion and bearing in mind that there are 7 specific factors for each renewable resource, the relative weight of each factor is equal to 14.3%. Figures 14 and 15 show the wind and solar suitability maps obtained when applying the criterion of equal weights.

Tables 6 and 7 compare the results obtained in the AHP models with the criterion of equal weights (see Figures 14 and 15) with the results obtained in the AHP model developed according to the criterion of expert-assigned weights (see Figures 9 and 10). A series of observations can be made after analysing the results. In both the wind and solar energy cases, the results obtained for areas with a low evaluation (<0.5) are highly sensitive, with respective variations of 11.49% and 35.31%. This would have a significant impact on the final result obtained in the hybrid model, where the hypothesis taken is to select areas with values above 0.5. Therefore, it was considered to be of fundamental importance to establish reasoned and expert-assigned weights for the different factors that intervene in the model, considering the particularities and requirements of the regions where it is applied.

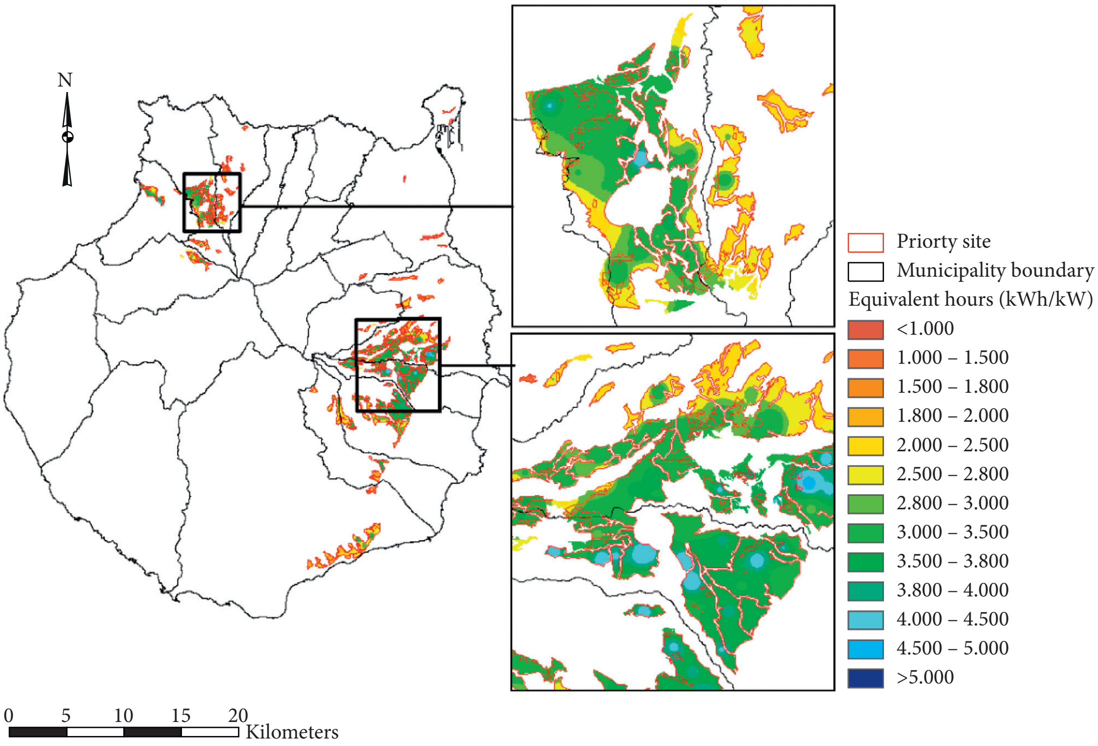


Figure 12: Wind equivalent hours.

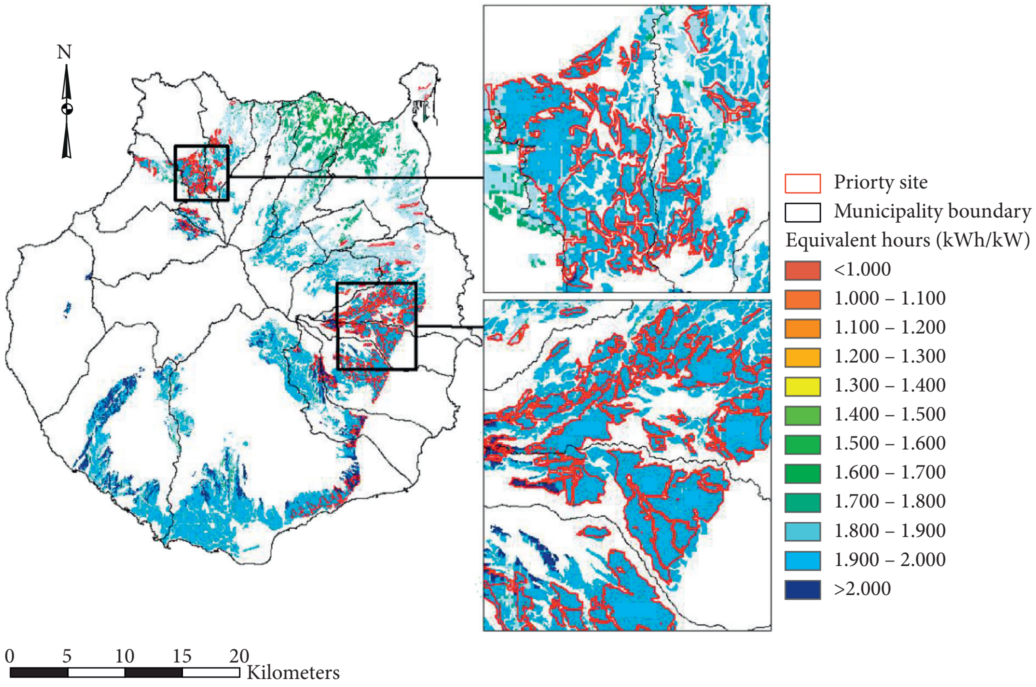


Figure 13: Solar equivalent hours.

3.4.2. Sensitivity to the Minimum Score Criterion to Determine Priority Areas in the Hybrid Model. Another of the critical aspects in the results of the model is the assignment of the minimum score for the selection of priority areas. With this in mind, a further sensitivity analysis was performed in which the results of available land area were compared according to the minimum score applied. In this respect, the results obtained for a minimum score of 0.5, used for the priority sitemap (see Figure 11), were compared with the surface areas that would be obtained if minimum scores of 0.6, 0.7, and 0.8 were applied.

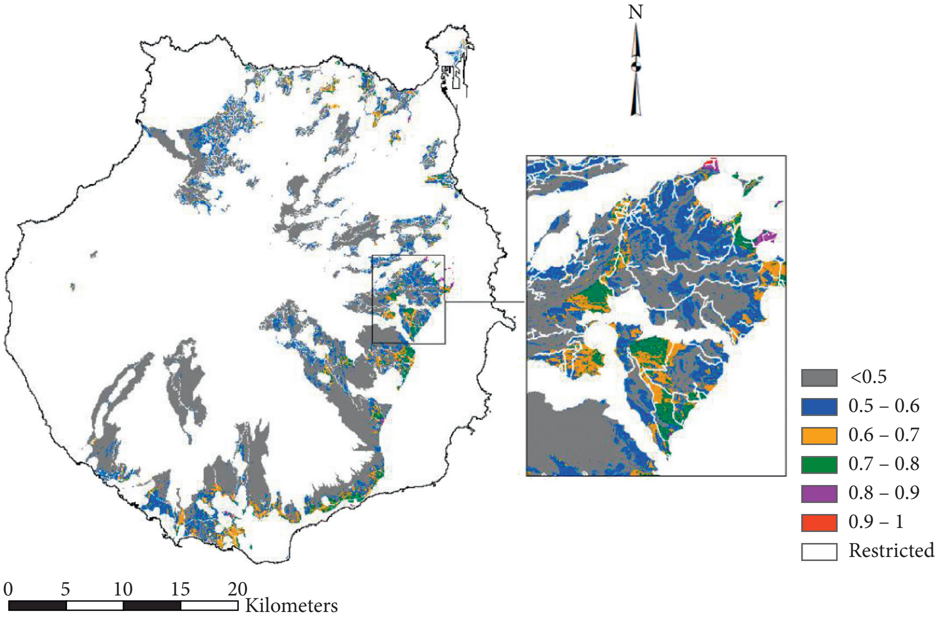


Figure 14: Wind suitability map (equal weights' criterion).

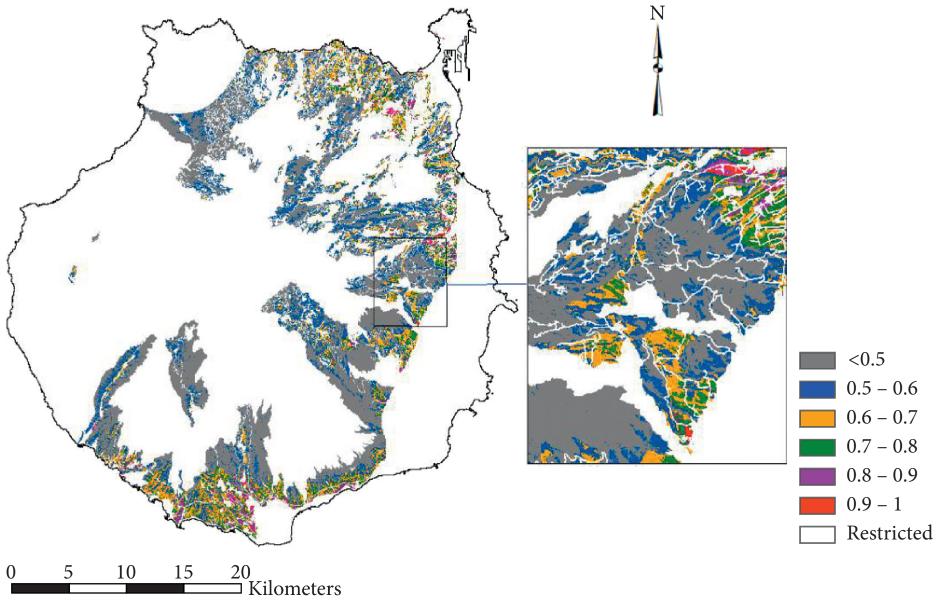


Figure 15: Solar suitability map (equal weights' criterion).

Figure 16 shows the graphic result of this comparative analysis.

Table 8 shows the numerical values obtained for the surface areas of Figure 16. It can be seen that the results for the hybrid model are markedly sensitive to the minimum score which is assigned for its generation. A 76.89% reduction in available surface area is obtained by simply changing from a minimum score of 0.5 to 0.6. Bearing in mind that the weights assigned to the factors of wind speed and solar radiation are the highest, increasing the constraint for the generation of the hybrid model entails increasing the importance of these factors in the results of the hybrid model. In this respect and considering separately the results obtained for the wind and solar models (see Figures 9 and 10), for this case study, wind speed was determined as the limiting factor in the results for the hybrid model.

Table 6: Wind sensitivity analysis results.

Suitability value score		AHP model (according to equal weights criterion)		AHP model (according to expert-assigned weights' criterion)		Sensitivity	
		km^2	%	km^2	%	km^2	%
Low	<0.5	197.08	69.80	229.51	81.29	−32.44	−11.49
Medium	0.5-0.6	49.85	17.65	37.34	13.23	12.50	4.43
	0.6-0.7	24.42	8.65	12.64	4.48	11.79	4.17
	0.7-0.8	10.37	3.67	2.81	0.99	7.56	2.68
High	0.8-0.9	0.60	0.21	0.04	0.01	0.56	0.20
	0.9-1	0.02	0.01	0.00	0.00	0.02	0.01
Total		282.34	100.00	282.34	100.00		

Table 7: Solar sensitivity analysis results.

Suitability value score		AHP model (according to equal weights criterion)		AHP model (according to expert-assigned weights criterion)		Sensitivity	
		km^2	%	km^2	%	Δ (km^2)	Δ (%)
Low	<0.5	202.67	52.11	65.36	16.81	137.31	35.31
Medium	0.5-0.6	93.99	24.17	150.40	38.67	−56.41	−14.51
	0.6-0.7	51.06	13.13	116.16	29.87	−65.10	−16.74
	0.7-0.8	30.81	7.92	44.14	11.35	−13.33	−3.43
High	0.8-0.9	8.93	2.30	9.06	2.33	−0.13	−0.03
	0.9-1	1.46	0.37	3.79	0.97	−2.33	−0.60
Total		388.91	100.00	388.91	100.00		

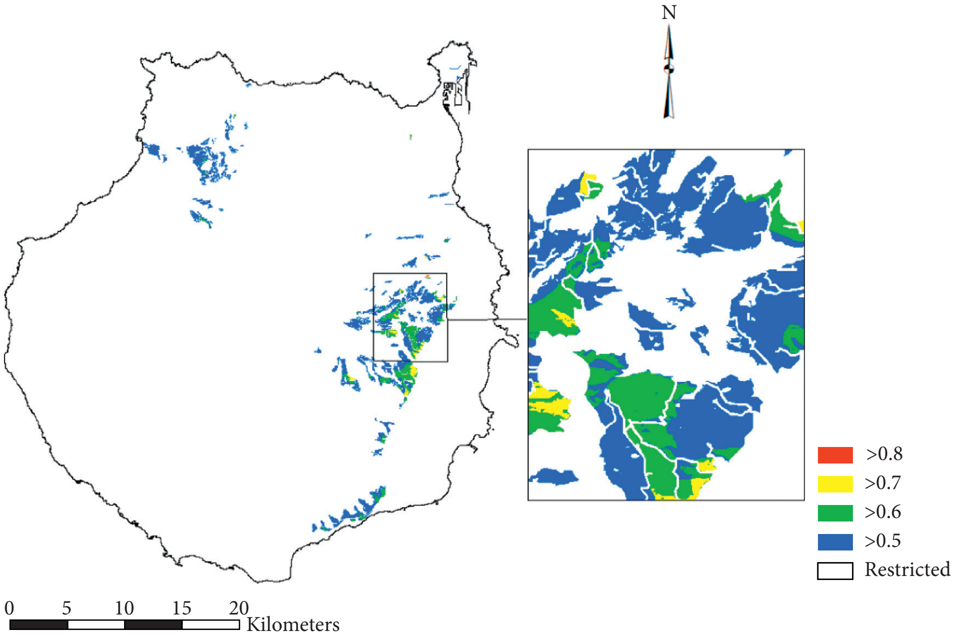


Figure 16: Sensitivity analysis map (minimum score for priority site).

Table 8: Sensitivity analysis results of minimum score for priority site.

Assigned value for minimum score	Sensitivity analysis		
	km^2 (%)	Δ (km^2)	Δ (%)
>0.5	45.26		
>0.6	10.46	−34.8	−76.86
>0.7	1.54	−43.72	−96.60
>0.8	0.03	−45.23	99.97

4. Conclusions

In this work, a GIS-MCDM-based model has been developed for use in territorial planning targeted at the joint implementation (hybrid model) of wind and solar installations for energy self-consumption. The model that has been developed can be applied to any territory. In this paper, the hybrid model that was developed was applied to the particular case of an insular electrical system (Gran Canaria, Canary Islands, Spain). The model can be incorporated as an energy planning tool to optimize the integration of renewable energy resources and to promote DEG systems, which are important goals in the framework of the development of sustainable and low-carbon energy policies.

To generate the model, territorial constraints were imposed and factors which were considered priority were identified in the siting of suitable areas. Weights were additionally assigned to each factor in accordance with their relative importance. For this ultimate requirement, consideration was given to the opinion of external experts connected to the energy sector and territorial and/or energy planning on the island. In this respect, a total of 9 factors were taken into consideration, related to technical, environmental, and economical aspects.

As a result of the models that were developed, potential sites were identified for the joint exploitation of wind and solar energy resources in areas relatively close to populated settlements with significant energy demand. These are urban and/or rural communities generally at some distance from the coast where wind and solar potential is high.

In the results of the model, the suitable areas were differentiated by the municipality in which they are located. In this way, the results can be incorporated in future territorial planning modifications at both island and municipality level.

Based on the assigned factors and weights, suitable areas were initially demarcated in terms of their potential for wind or solar energy exploitation. The demarcated areas were evaluated on a scale of 0 to 1, with 0 equivalent to zero viability and 1 to high viability. For the results of the hybrid model, which are identification of the areas suitable for joint solar and wind energy exploitation, the areas selected were those with a score above 0.5 for both wind and solar exploitation. In this way, suitable areas were identified in 12 of the 21 municipalities of the island. The total demarcated surface area amounted to 45.3 km^2, which corresponds to approximately 3% of the total area of the island.

In the results of the models, two elements were considered to be critical: the allocation of weights to the different factors and the minimum score considered for the generation of the hybrid model. With this in mind, an additional sensitivity analysis of the results to these two elements was performed. With respect to the weights assigned to the different factors, the results that were obtained on the basis of an expert-assigned weights criterion (see Figures 9 and 10) were compared with those obtained on the basis of a criterion of equal weights for all factors (see Figures 14 and 15). From the results obtained for the individual wind and solar models, a decrease of 14.13% was observed in the wind model for areas with a score below 0.5, and in the solar model, an increase of 210% (Tables 6 and 7, respectively) was observed. These results would have a significant impact on the results of the definitive hybrid model. With respect to the sensitivity of the results to the chosen minimum value for the generation of the hybrid model, it was observed that a change from 0.5 to 0.6 would result in a decrease in the available suitable area in the hybrid model of 76.89%, from an initial 45.3 km^2 to 10.46 km^2. In short, the results of the hybrid model are highly sensitive to the two elements considered, which should therefore be carefully established according to the case study in question.

Abbreviations

λ_{max}: Largest eigenvalue (equation (1))
AHP: Analytic hierarchy process
CI: Consistency index (equation (1))
CR: Consistency ratio (equation (2))
DEG: Distributed electricity generation
DEM: Digital elevation model
EH: Equivalent hours (kWh/kW and kWh/kW_p for wind and solar energy, respectively)
GIS: Geographical information systems
GRAFCAN: Public enterprise run by the autonomous government of the Canary Islands for the production and management of geographic and territorial information
ITC: Instituto Tecnológico de Canarias; Technological Institute of the Canary Islands, an R & D enterprise run by the autonomous government of the Canary Islands
MCDM: Multiple-criteria decision-making
INECP: Integrated national energy and climate plan 2021–2030
RE: Renewable energy
RI: Random index, average CI of the randomly generated comparisons (equation (2))
STP-32: Special territorial plan of the island of Gran Canaria.

Data Availability

The data used to support the findings of wind speed are available at http://www.itccanarias.org/recursoeolico/ (Instituto Tecnológico de Canarias (ITC): Technological Institute of the Canary Islands), solar radiation are available at http://www.idecanarias.es/listado_servicios/mapa-radiacion-solar (Spatial Data Infrastructure of the Canary Islands), visual impact are available at http://www.gobiernodecanarias.org/cultura/actividades/cantierradecult09/10PATRIMONIO%20CULTURAL.pdf (Autonomous Government of the Canary Islands), slope/orientation/road/potential self-consumption is available at http://tiendavirtual.grafcan.es/index.jsf (Cartográfica de Canarias, S.A.- GRAFCAN), territorial planning are available at https://www.idegrancanaria.es/catalogo (Spatial Data Infrastructure of Gran Canaria), demand are available at https://www.ine.es/ (Spanish Statistical Office), protected areas are available at https://www.miteco.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ENP_Descargas.aspx (Ministry for Ecological Transition of the Government of Spain) and http://catalogo.idecanarias.es/geonetwork/srv/spa/catalog.search#/search?resultType=details&inspiretheme=Lugares%20protegidos&from=1&to=20&sortBy=relevance (Spatial Data Infrastructure of the Canary Islands), and roads/urban area/water bodies/sea-land limits/airports are available at http://tiendavirtual.grafcan.es/index.jsf (Cartográfica de Canarias, S.A.- GRAFCAN) and https://planesterritoriales.idegrancanaria.es/config/planes.xml (Gran Canaria Regional Government).

Disclosure

No funding sources had any influence on study design, collection, analysis, or interpretation of data, manuscript preparation, or decision to submit for publication.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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