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A method based on GIS techniques to assess renewable energy self-consumption capacity. A case study

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ABSTRACT

The exploitation of renewables through energy self-consumption installations is one of the key strategies for the decarbonisation of energy systems and the promotion of distributed electricity generation. Wind and solar photovoltaic energy are two of the renewable sources commonly used to generate electricity for self-consumption. One of the key limitations in the exploitation of medium-large scale wind and solar photovoltaic installations is their compatibility with the geographical characteristics of the territory. In this paper, a method has been developed using GIS techniques to precisely identify the optimal locations that maximise the energy yield of such installations for electrical energy self-consumption. In the implementation of the method, criteria related to the topographical characteristics of the terrain (slope, orientation and shading, etc.), to the energy potential (capacity factor, etc.), and to logistical questions are jointly considered. The method is applied to a case study on the island of Gran Canaria (Spain). The results derived from the application of the method show the importance of detailed consideration of the topographical characteristics. This aspect is even more important in regions/countries with limited availability of useful territory for these types of installations, and is therefore key in the elaboration of energy planning strategies.

1. Introduction

Directive 2018/2001 of the European Parliament and of the Council [1] set the binding global target of achieving a renewable-sourced energy share of 32 % of the gross final energy consumption of the European Union by 2030. For this end, one of the new strategic lines established by this European regulatory framework is to encourage the self-consumption of electricity from renewable energy sources. In this sense, it distinguishes between 3 figures that can promote installations of this kind: i) renewables self-consumers; ii) jointly acting renewables self-consumers; and iii) renewable energy communities. In order to maximise the integration and exploitation of renewable energy sources, research studies are required which focus on territorial planning and the assessment of the capacity of the different renewable energy sources according to the characteristics of the territory, the renewable energy potential, the electricity system of the territory, etc.

Several works have been published in the literature in which spatial planning models are developed of wind and solar photovoltaic (PV) energy installations, generally through the application of *Multiple Criteria Decision Making* (MCDM) based on *Geographic Information Systems* (GIS) [2]. The results of these studies provide valuable information that can subsequently be used to assess the economic viability of this type of installation. For this reason, such studies are commonly complemented by calculation of the electrical energy potential in the areas identified in them as suitable for exploitation. In the case of solar PV energy, it is usual to apply the formula given by Gastli and Charabi to calculate the electrical energy potential [3]. This calculation is based on four factors: (a) the average annual solar radiation per unit area; (b) the total area selected as suitable: (c) a land occupancy factor indicating the fraction of the selected area that can be covered by solar panels; and (d) the efficiency with which the selected photovoltaic technology converts sunlight into electricity. The first two factors depend on the geographical characteristics of the area under study and are obtained, respectively, from the *solar radiation* map (Wh/m^2/day) and the *land suitability* map obtained from a previously performed MCDM-GIS analysis. In almost all the works reviewed, a value of 0.7 is assigned to the land occupancy factor. That is, a 70 % land occupation is assumed with a minimum shading effect on the PV panels. Although determination of this factor is key to evaluating the installable PV power and the electrical energy it can generate, this value is assigned randomly, without

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justification and with a generic estimate, and without considering that the area that can be occupied by the PV installations depends on the specific topographic conditions of each area. For its part, the efficiency factor of the system differs according to the criteria adopted in each study carried out. For example, in Ref. [4] the efficiency values assigned to each PV technology analysed in the study were made on the basis that Oman is a region of high temperature and low direct solar radiation. In some studies, an efficiency value was assumed based on the criterion established by Ref. [5] in which overall system efficiency is considered to be influenced by dust and dirt losses in the PV array, the electrical installation in direct current, temperature variations, the module tilt angle, inverter efficiency and the solar reflection of the array. This criterion was applied in Ref. [6] to a large-scale on-grid solar system in Algeria, in Ref. [7] using single-crystalline and polycrystalline silicon cell technology, and in Ref. [8] considering three scenarios based on three efficiency values of 10, 15 and 20 % in Khuzestan province in Iran. In Ref. [9], the applied efficiency value of 16 % is the mean value of commercial silicon modules according to the International Energy Agency. This criterion was also applied in large scale territorial contexts in Tunisia [10] and in island territories such as Mauritius [11]. In some works, integrated software and simulation methods have also been used to obtain solar radiation and panel performance data. For example, in Ref. [12] the authors applied PVsyst, which is extensively used by the PV energy industry in Israel, and in Ref. [13] Skelion was used for the spatial planning of PV plants in Çanakkale province in Turkey. In Ref. [14], an adaptation was made to the Gastli and Charabi formula by georeferencing the values of the electrical power generation potential and integrating the total available area and the land occupancy factor into a single coefficient. In this case, the module efficiency factor is assumed to be that declared by the manufacturer.

Regarding wind energy potential assessment, and according to the literature reviewed, the most commonly employed procedure is as follows: (a) determination of the areas available for wind turbine installation; (b) calculation of wind turbine density; and (c) calculation of the total energy production based on the energy generated by each wind turbine. As in the case of PV energy, determination of the available areas depends on the geographical characteristics of the area under study and is obtained from the *land suitability* map resulting from a previously performed MCDM-GIS analysis. Wind turbine density depends on the number of machines to be installed in the available area. To calculate this number, consideration needs to be given to the potential for mutual interference if they are located too close to each other (wake effect), reducing the efficiency of energy capture in the whole wind farm [15]. The calculation of the number of wind turbines is therefore of fundamental importance and must take into account the spacing between machines which, in turn, is a function of rotor diameter (D). Calculation of total energy production is estimated based on the number of turbines that can be installed and the annual production of each turbine. These parameters differ in the different works reviewed depending on the type of wind turbine. In Ref. [16], for example, the wind energy potential in coastal areas of Taiwan was determined calculating the capacity of each turbine based on [17] and a wind turbine density of 15 per km ^{2} for 60 m rotor diameter types, assuming a 3D x 6D machine spacing. In Ref. [18] the wind energy potential in Serbia was estimated as the sum of the product of the number of wind turbines in each suitable area and the annual efficiency of a machine in the same location, considering a turbine land occupancy area of 0.576 km^2, a rotor diameter of 120 m and machine spacing of 8D x 5D. In Ref. [19], a wind energy potential study for northwestern Iran was carried out in which a 10D x 10D spacing was selected for turbines with a rotor diameter of 47 m, resulting in an installation capacity potential of 1.4 MW/km^2, with annual energy production for suitable areas estimated in accordance with [20]. In Ref. [21] annual wind energy production in China was determined based on an equation which integrates the following parameters: power coefficient, matrix efficiency of a wind farm considering the distance between wind turbines, capacity factor, installed power density, time in hours available per year, and the area suitable for wind turbine installation. In Ref. [22] in which the wind energy potential in Balıkesir (Turkey) was calculated, the authors determined the density of installable machines of 120 m diameter by multiplying the total area (km^2) by the constant value of 6.6138 (according to a 7D x 3D distribution) and adding 2. In this case, the power generated by the turbine is a function of air density, average wind speed, the power coefficient (0.40) and the area swept by the turbine blades.

There is also growing interest in hybrid combinations of solar and wind power to increase electricity generation and minimise the non-dispatchable nature of the two separate installations [23]. In this regard, we will present some works that present methods to determine wind and solar electrical energy potential together. In general, the reviewed works also use the formula given by Gastli and Charabi for the calculation of solar PV electrical energy, arbitrarily considering a land occupancy factor of 70 %. In the case of wind-sourced electrical energy, the calculation was performed in Ref. [20] of the installation capacity in Afghanistan by districts according to the available area (km^2) considering a power density of between 2 and 2.78 MW/km^2. In Ref. [24] a study was undertaken in India, applying the same methodology as in Ref. [20] but in this case taking a power density of between 4.4 and 7.2 MW per km^2. In Ref. [25]an assessment was made of the wind potential in Far North Queensland (Australia), with estimated wind power density values of 7.2 MW/km^2. In Ref. [26] the wind energy potential in Tunisia was calculated considering an equal spacing factor of 10D and determining an installed capacity potential of 4 MW/km^2.

From the scientific literature reviewed, it was found that the installable wind capacity is commonly estimated using very generic procedures, based on values of wind turbine density and/or wind power per unit of available surface area. In other words, the relative location of each wind turbine with respect to the rest in terms of the topographical characteristics of the area is not taken into account, nor is the effect of wind direction on the optimal distribution of the machines and on maximisation of the electrical energy generated by the whole. As mentioned, a similar approach is used to estimate the installable PV power in a given area. In the latter case, based on the available surface area, a generic value is adopted as the land occupancy factor, equivalent to 70 % of the former. Generally, no consideration is given to differing topography in the area under study, with its variations in slope and orientation. These factors affect, for example, that the terrain itself generates shading effects that limit the installation of PV infrastructures.

Another generalised characteristic detected in the studies reviewed is that they are fundamentally oriented towards the evaluation of wind and/or solar PV power in large territorial contexts, and with the aim of large-scale exploitation for direct connection to electricity transmission networks. No studies have been found where a specific assessment is made of wind and PV power for energy self-consumption, which promotes distributed generation with renewables. The establishment of specific community guidelines for energy self-consumption [27], self-consumption installations exploited by energy communities on a medium to large scale [28], strategies for electrical energy decentralization and the promotion of distributed generation [29], accurate demand management and allocation [30], and the development of precise studies which analyse and optimize the compatibility of this type of facility with the geographic characteristics of the territory are key strategic lines to maximise the contribution of non-dispatchable renewable energy sources to satisfying the electricity demand of any country and/or region. This aspect can be even more important in territories with not very robust electrical systems, such as those that can be found in islands without connections to other territories, and/or limited surface area availability.

In order to fill this knowledge gap, a new method is developed in this work, through the application of GIS techniques, to precisely identify the optimal locations that maximise the energy yield of such installations for electrical energy self-consumption. The method makes the following original contributions: (i) it assesses the wind and solar PV energy capacity that can be installed for self-consumption of electricity on a medium to large scale in a specific territory; and (ii) for its implementation, various criteria/restrictions related to topographic (slopes, orientations and shadows of the terrain) and energy (wind and solar capacity factors, electricity demand of the system) aspects, as well as others concerning the logistics associated with the installation of this type of infrastructure are jointly considered. As a result of the application of the method, the land occupancy factor of PV installations and the optimal wind turbine distribution are precisely evaluated. In this way, the installable wind and solar power, the electrical energy that can be generated from the renewable sources, as well as the degree of coverage of electrical energy demand in a self-consumption regime are calculated. The large-scale integration of non-dispatchable renewable energy sources can affect the stability and quality of electricity systems [31]. This method is intended to serve as a strategic tool to promote the integration of renewable energy sources in a self-consumption regime and, hence, distributed electricity generation.

The method is applied to a case study on the island of Gran Canaria, the second most populated of the Canary Islands (Spain). It has an isolated, not very robust electricity system, which has no connections to the other islands or to the mainland, making it highly sensitive to fluctuations in the generation and/or demand of the electricity system.

2. Materials and methods

Fig. 1 shows the method developed and applied in the study of the present paper. The management, analysis and visualization of the data and results were done thorough a GIS implemented in the ArcGIS 10.8 software. The Reference System used was REGCAN95/UTM zone 28 (EPSG code 4083).

Gran Canaria has a total surface area of 1508 km^2, of which practically 40 % has restricted use as it forms part of either the Canary Islands Network for Protected Natural Areas or the EU Nature 2000 network [32]. According to the latest official published data, the island has a total of 857,171 residents [33], with an electrical energy demand of 3180.7 GWh and a renewable contribution of 21 % [34], some way below the 45 % target established by the Canary Government in its strategic planning for 2025 [35].

2.1. Criteria considered for the wind installations

As indicated in the Introduction section, the theoretical installable wind power is usually determined considering the wind turbine density in the previously selected area. In this study calculation of the installable wind power is based on a detailed analysis considering a hypothetical spatial distribution of the machines according to criteria related to the specific characteristics of each area. In this sense, the location of each wind turbine is considered according to the following criteria: (i) wind capacity factor (WCF); (ii) the slope of the terrain; (iii) minimization of energy losses due to the wake effect; and (iv) characteristics of the road infrastructure that will limit the maximum dimensions of the wind turbine to be installed due to potential logistical problems.

The first criterion used to evaluate the wind energy potential of each area was the WCF (in kWh/kW). This value was extracted from the work done in Ref. [36]. This shows the WCF value in each area identified as a so-called priority site. Regarding the second criterion, areas with steep slopes were discarded as they contribute to higher economic costs. The appropriate location of the turbines in the wind farm has a direct impact on the installation's investment, operating and maintenance cost as well as its energy yield [26]. Wind turbine spacing was determined considering the minimization of energy losses between them due to the wake effect [21] and the optimization of the installable power in the available terrain [39]. In this regard, taking into account the wind characteristics in the archipelago, the Canary Islands Government established in Article 3 of Decree 6/2015 [40] the minimum 'exclusion area' for wind turbine installations. In this Decree, the 'exclusion area' refers to the area in which only one wind turbine can be installed and is demarcated by a contour whose vertices are the points of intersection generated by drawing two lines parallel to the dominant wind direction at a distance of two diameters on both sides of the rotor axis, and two lines perpendicular to the dominant wind direction at a distance of eight diameters from the axis of symmetry of the wind turbine tower leeward and windward. Taking into account the available land constraints in an insular territorial context, the above described minimum exclusion area was used for the case study presented here.

The area under study is a volcanic island with very abrupt topography where the characteristics of the road network to the priority sites are varied, adapted to the corresponding orography. Bearing in mind that the size of the wind turbine determines the cost and viability of the logistics for its transport, two wind turbine types of different size were

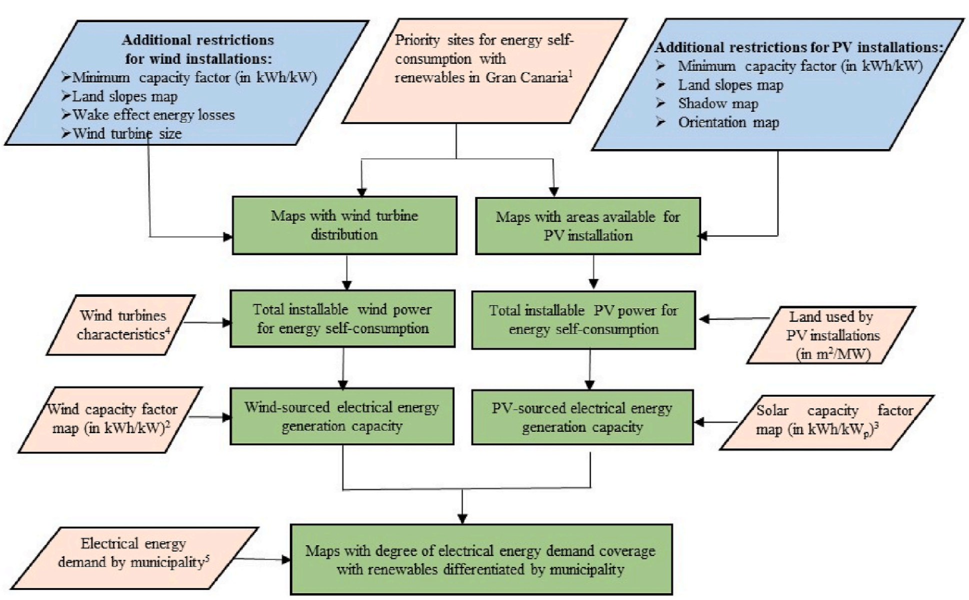

Fig. 1. Method developed for the optimization of energy self-consumption with wind and photovoltaic energy.
[1,2,3] See Figs. 11, 12 and 13, respectively, in Ref. [36]. [4,5] See Refs. [37,38], respectively.

considered: Type 1, with a power range of 2–3 MW and Type 2 with a power range of 800–900 kW. According to the latest official data, practically 80 % of the wind turbines installed in recent years in the Canary Islands are within these power ranges [34]. Taking into account the technical characteristics of the existing wind turbines on the market for these power ranges [37], average rotor diameters of 90 and 50 m for Types 1 and 2, respectively, were considered for the present case study.

2.2. Criteria considered for the photovoltaic installations

As indicated in the Introduction, one of the drawbacks observed in the literature for installable PV power evaluation in a territory is that this is usually determined applying a mean land occupancy factor to the total available surface area. This criterion significantly conditions PV power evaluation, as the orographic characteristics of the territory vary and can affect not only the evaluation of the available useful surface area, but also the energy yield of this type of installation. To overcome this drawback, the calculation of the installable PV power in this work does not start with the application of such a factor but instead is based on a detailed analysis of the territory using GIS techniques, considering a hypothetical distribution of areas that can be covered by solar panels selected according to five criteria: solar capacity factor (SCF), land use by PV installations (in m^2/MW) and the shading, orientation and slopes of the terrain.

The SCF aims to evaluate the annual equivalent specific energy generated in a given area by a PV installation (in kWh/kW). As in the case of wind energy and the WCF, the SCF value was extracted from the work carried out in Ref. [36].

It is evident that the PV power reaching a given location will decrease if it is shaded. Therefore, consideration was given to selecting those areas with a smaller area of land covered by shade. However, the shade will of course not be constant during the day as the sun's position varies, appearing above the horizon (sunrise), reaching its maximum height, and then beginning to descend towards the horizon in the west (sunset). Furthermore, the sun is not at the same height above the horizon throughout the year. In summer (in the northern hemisphere) it is higher above the horizon than in winter. So, the amount of shade will also depend on the height of the sun throughout the day which also differs over the course of the year. Taking the above into account, in this study we selected those areas not occupied by shade both at dawn and dusk (which is when the greatest shadow is cast) in the spring and autumn seasons (when the sun is at mid-height).

Regardless of the shadows cast on the territory, south-facing areas receive the sun's rays for a longer time and at a steeper angle than north-facing areas in the northern hemisphere [13]. For this reason, slope orientation was also taken into account as a third criterion when assessing the most suitable areas for locating this type of installation.

With regard to the slope of the terrain, areas with steep slopes were discarded as they contribute to higher economic costs due, among other aspects, to the need for land development work and the resulting environmental impacts.

As a result of the geographical latitude of the Canary Islands, the usual average inclination of the modules in PV installations for energy use optimization is 25°-30°. This means that the specific land requirements are lower than in other areas with higher latitudes, as the latter will require greater distances between lines of modules to avoid shadows between them. The average specific surface area occupied by PV installations in the Canary Islands at present is approximately 12000 m^2/MW [41]. This value, which is used for the purposes of the present case study, is among the lowest values recorded for PV farms in the report of the International Renewable Energy Agency [42].

3. Results and discussion

Based on the developed method, the initial data and hypotheses established, the results obtained, and their novel contributions are described in the following subsections.

3.1. Evaluation of available wind power for self-consumption

3.1.1. Criterion 1: wind capacity factor (WCF)

For the distribution of wind turbines in the priority sites, the benchmark WCF values were those taken from Ref. [36]. To ensure an acceptable economic viability of the wind farms, and taking into account that there are many areas with a high WCF, areas with an annual WCF of less than 2500 kWh/kW were initially discarded. It should be noted that, according to the latest official data from the government of the Canary Islands [34], the mean annual WCF of the wind farms currently in operation on the island of Gran Canaria is 3220 kWh/kW.

3.1.2. Criterion 2: land slope

The analysis of the slope in each zone was carried out using the DTM02 of Spain's National Centre for Geographic Information (CNIG by its initials in Spanish) [43]. From this digital terrain model (DTM), with a mesh size of 2 m × 2 m that allows a detailed analysis of each zone, a digital slope model (in %) was obtained. For the case study of this paper, areas with slopes greater than 50 % were excluded.

3.1.3. Criterion 3: wind turbine spacing

As indicated in section 2.1, the exclusion area for each wind turbine is a function of two parameters: the rotor diameter and the predominant wind direction in the area. The criterion for the choice of wind turbine type in each part of the priority sites was conditioned by the degree of difficulty of access via the existing road network. Type 1 was considered for the more accessible areas, and Type 2 for the rest. In this way, exclusion areas were drawn for each wind turbine, taking their geographical coordinates as reference data.

By way of example, considering simultaneously the constraints established in the three criteria indicated above, Figs. 2 and 3 show the proposed final distribution of wind turbines in a specific part of one of the priority sites.

3.2. Estimation of available photovoltaic power for self-consumption

3.2.1. Criterion 1: solar capacity factor (SCF)

Fig. 4 shows the map with the SCF for the priority sites. This figure is a result obtained by the authors in Ref. [36]. In that study, the SCF was defined as equivalent hours, in kWh/kW. As can be observed, practically all parts of the priority sites have SCF values above 1800 kWh/kW. For this reason, for the purpose of the case study of the present paper the few zones with SCF values below that value were discarded.

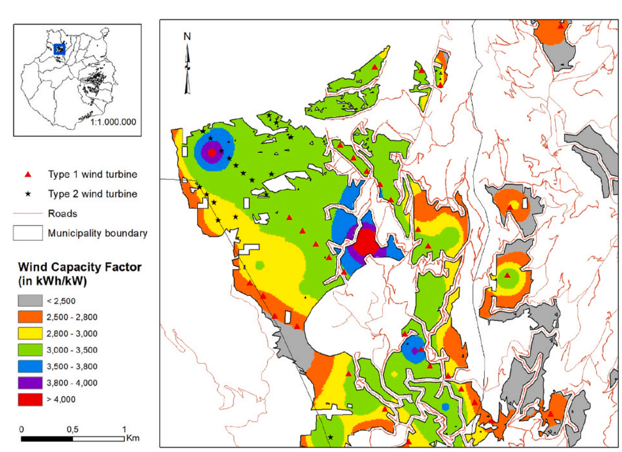

Fig. 2. An example of a wind capacity factor map with the optimal wind turbine distribution for a specific part of the priority sites.

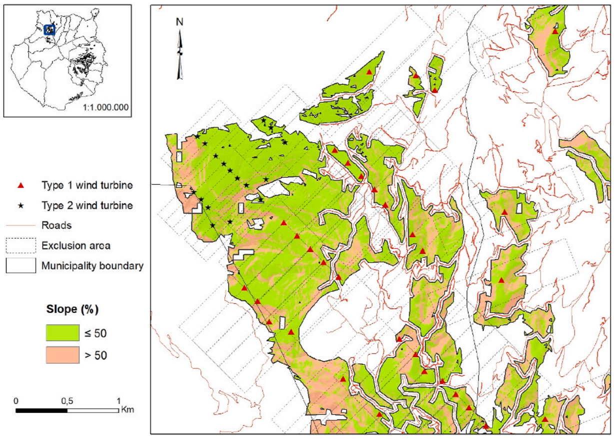

Fig. 3. An example of a land slope map with the optimal wind turbine distribution for a specific part of the priority sites.

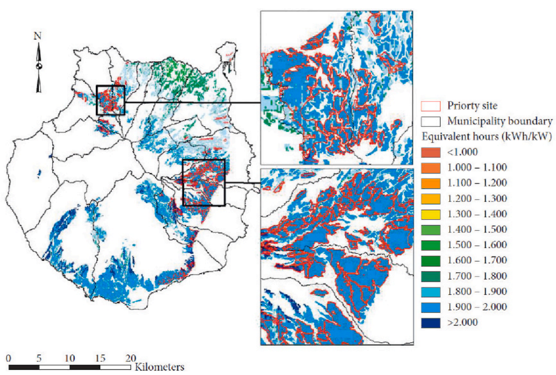

Fig. 4. Solar capacity factor map [36].

3.2.2. Criterion 2: land shade

To evaluate this factor, a *hillshade model* was developed for the territory using ArcGis, combining the orography of the study area with the positioning of a hypothetical light source, in this case based on the sun's position. Two elements were required for the development of the hillshade model: a DTM and the sun's coordinates. The DTM used was obtained from the DTM02 of the CNIG, while the sun's position was calculated from the coordinates of its position with reference to the horizon plane, height (h) and azimuth (A), according to Eq. (1) and Eq. (2). Given that these coordinates vary continuously, it was necessary to model this variable for specific points in the spring and autumn seasons, which is when the sun has average and equal values of these two coordinates. In this case, since the exact coordinates of sunrise and sunset are of no use as the sun has no altitude and will not cast a shadow, it was decided to calculate the azimuth and altitude of the sun at 5 h before noon (sunrise) and 5 h after noon (sunset).

$$\sin h = \sin \delta \sin \varphi + \cos \delta \cos \varphi \cos H \tag{1}$$

$$cosA = \frac{\sin \varphi \ sinh - \sin \delta}{\cos \varphi \ cosh} \tag{2}$$

where h = height, A = azimuth, φ = the site's latitude, δ = the sun's declination, and H = the hour angle.

The hillshade model represents shadow and light with shades of grey associated with integers from 0 to 255 (increasing from black to white). The cells in shadow are coded with 0, while the other cells are coded with integers from 1 to 255. Therefore, to accurately identify the shaded areas, all values greater than or equal to 1 were reclassified to a class we call sun (represented in white) and values below 1 to a class we call shadow (represented in black). This results in a map in which the black areas are in shadow and the rest in sun.

3.2.3. Criterion 3: orientation

To model the direction of the slopes in the territory, the Arcgis *Aspect* tool was used. This tool enables calculation of the orientation of the slopes from the DTM of the territory. The values in each cell indicate the geographical direction in which the slope surface is oriented at each point. It is measured clockwise in sexagesimal degrees, where 0^o is N. In this work, the orientation of the slopes was obtained from the DTM02 of the CNIG, so that the direction of the plane calculated in the model represents the orientation of the slope of each 2 m × 2 m cell. Taking the above into account, areas with a southern orientation between 135^o and 225^o were considered suitable.

3.2.4. Criterion 4: slope

As in the case of wind energy, the analysis of the slope in each area was carried out using the DTM02 of the CNIG, obtaining a digital slope model (in %). For the case study, areas with a slope below 50 % were considered suitable, with this factor applied in conjunction with the previously described southern orientation. This 50 % value was adopted for two reasons. Firstly, the topography of the area under study is characterised by an orography with areas of steep slopes due to its volcanic origin. In this sense, if the value of the slope is overly restricted, this could mean that areas with high potential for renewable resources exploitation would be wasted. Secondly, for PV installations where the slope characteristic is more critical, and also taking into account the latitude of the study area, a slope value of 50 % favours adaptation of the inclination of the modules to the slope of the hillside.

3.2.5. Criterion 5: minimum area considered

With the aim of avoiding the excessive visual impact that would be caused in the priority sites by a large number of PV installations in small plots, it was decided to restrict their use to plots with a capacity above 2.5 MW. In this regard, taking into account the specific land occupancy data established in this study, plots with areas of less than 30,000 m^2 were excluded from the analysis.

Based on the above described methodology and taking into account the different constraints, the optimal locations for PV installations were identified and are shown in Figs. 5–8 for priority sites on the basis of the SCF, shadow, orientation (aspect) and land slope maps, respectively.

For the case study, the total surface area of the optimal locations for PV facilities is 7.2 km^2, which corresponds to 15.9 % of the 45.3 km^2 initially available in the priority sites established in Ref. [36]. This relative value is considerably less than the 70 % which, as indicated in the Introduction, is commonly used in the literature as a land occupancy

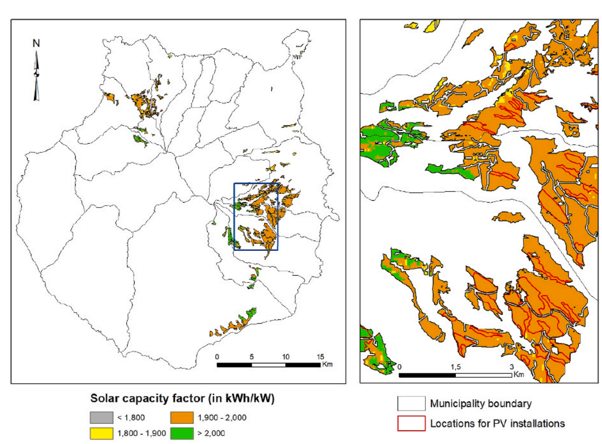

Fig. 5. Solar capacity factor map with the optimal locations for PV installations.

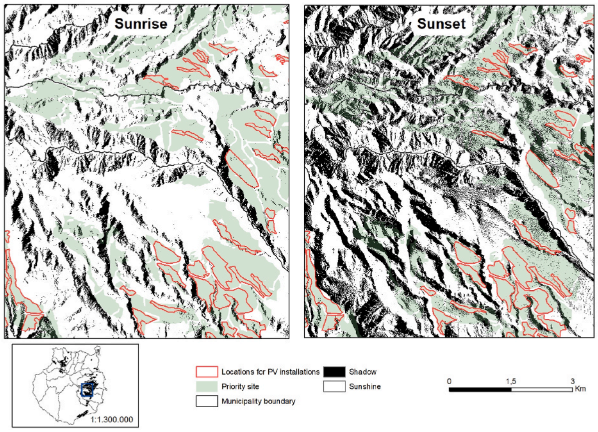

Fig. 6. An example of a shadow map with optimal locations for PV installations for a specific part of the priority sites.

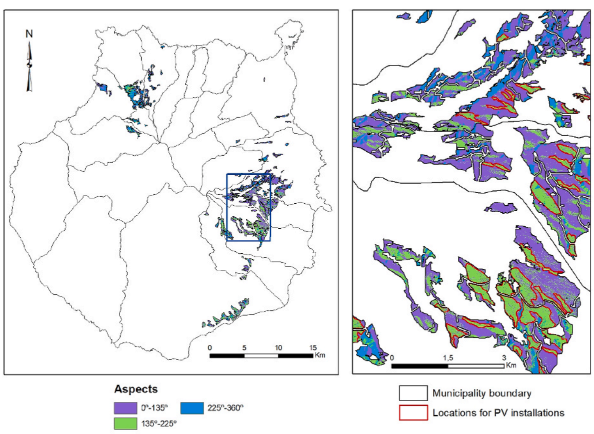

Fig. 7. Slope orientation (aspect) map with the optimal locations for PV installations.

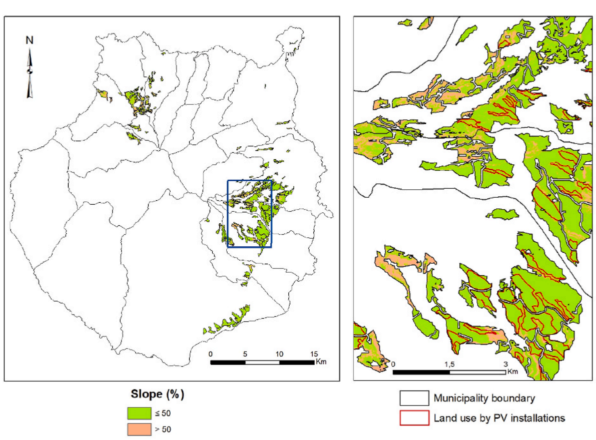

Fig. 8. Slope map with the optimal locations for PV installations.

factor to estimate PV potential. In short, it can be concluded from the results obtained employing the proposed methodology that a detailed technical analysis of the orographic characteristics of the terrain to obtain a final demarcation of the optimal locations for PV installations and wind turbines is of fundamental importance.

By way of example, Fig. 9 shows the results of both the optimal wind turbine distribution and the optimal locations for PV installations in specific areas identified as priority sites.

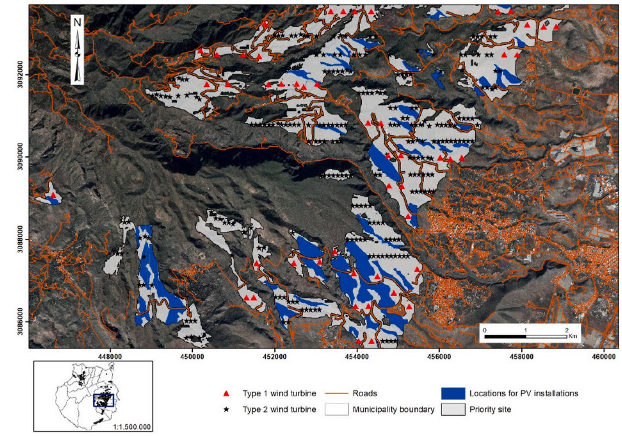

Fig. 9. Joint map of optimal wind turbine distribution and optimal locations for PV installations.

3.3. Degree of coverage of electrical energy demand with wind and PV renewables

Based on the proposed method and in accordance with the established criteria, the distribution of wind turbines and the locations for the PV facilities were optimised for all areas of the priority sites. With this information, and based on the unit power of each wind turbine and the surface area occupied by PV installations, the total installable renewable power was calculated for each municipality (Table 1).

Using the installable wind and PV power data and the wind and solar capacity factors for each geographic location (Figs. 2 and 4), the available renewable energy for self-consumption was calculated along with, based on Eq. (3), the equivalent capacity factor (ECF):

$$ECF = \frac{Available\ renewable\ energy\ for\ self - consumption}{(Wind\ power + PV\ power)} \quad (3)$$

The ECF value of the wind-PV installations differs depending on the municipality in which the priority site/s is/are located. This is because the wind and PV power distribution is different in each municipality and the wind and solar capacity factors vary depending on the geographic area in question.

The electrical energy demand data for each municipality (see Table 1) include residential, commercial and industrial demand and were taken from the publicly available *Datadis* platform [38], developed by Spain's national electricity distributors.

Fig. 10 shows a map of self-consumption capacity with wind and PV energy to cover electricity demand in the different municipalities. As can be seen, in 9 of the 12 municipalities available renewable energy could supply 100 % of the electricity demand.

If we compare, for each municipality, the available renewable energy for self-consumption data and the energy demanded, the total energy that could be supplied by renewable energy installations under a self-consumption regime is 1383.6 GWh. This is equivalent to 43.5 % of the total electricity demand of the island of Gran Canaria [34]. In this way, electricity generation is promoted through sustainable energy sources exactly where it is demanded, thus encouraging distributed electricity generation and, consequently, improving the stability of the system and the quality of the supply.

3.4. Sensitivity analysis

One of the critical aspects affecting the results obtained through application of the proposed methodology is the maximum value adopted for the land slope. This geographical characteristic has been widely

Table 1
Renewable energy capacity for self-consumption.

Name of the municipality	Id.	Wind power (MW)	PV power (MW)	Energy demand of the municipality (MWh)	Available renewable energy for self-consumption (MWh)	ECF (MWh/MW)
Agaete	1	29.3	9.4	14,028.0	112,928.3	2918.0
Agüimes	2	94.4	214.9	364,850.8	729,220.2	2357.6
Artenara	3	19.3	9.7	1676.4	75,893.3	2617.0
Gáldar	4	83.6	72.2	84,552.6	400,665.4	2571.7
Ingenio	5	109.2	64.3	68,582.2	516,535.2	2977.1
Las Palmas de G.C.	6	0.0	12.7	1,142,572.3	23,582.8	1856.9
San Bartolomé de Tirajana	7	32.2	91.1	562,132.6	265,447.2	2152.9
Santa Brígida	8	0.0	3.9	38,577.1	7220.2	1851.3
Santa Lucía de Tirajana	9	21.8	40.0	138,151.9	143,418.6	2320.7
Santa María de Guía	10	11.5	7.0	43,109.9	46,129.9	2493.5
Telde	11	143.0	66.4	336,375.6	574,691.2	2744.5
Valsequillo	12	2.3	8.5	21,520.2	22,285.7	2063.5
TOTALS		546.6	600.1	2,816,129.6	2,918,018.0	

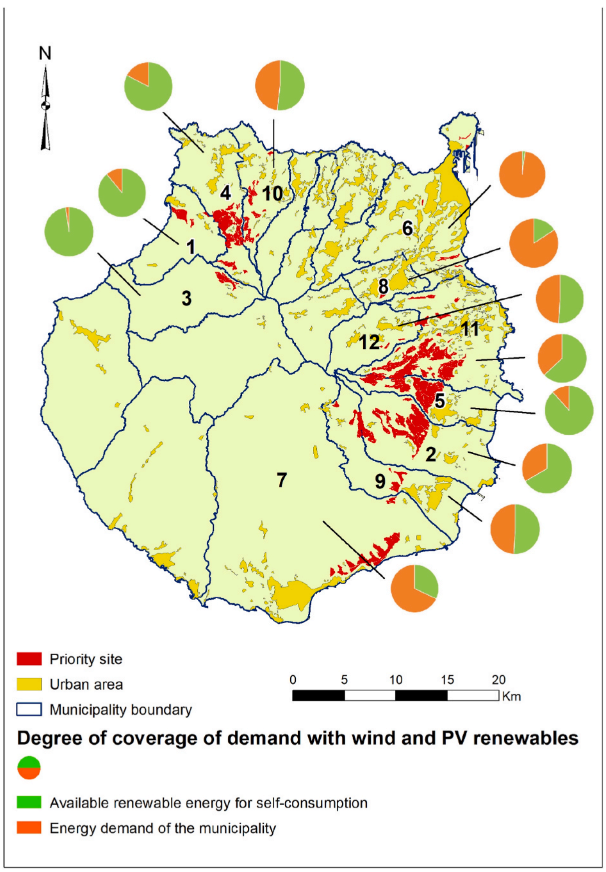

Fig. 10. Degree of coverage of electricity demand with renewable energy for self-consumption.

acknowledged in the literature as a constraint in both wind (e.g., see Ref. [44]) and PV installations (e.g., see Ref. [13]). Evidently, the slope value conditions, among other aspects, the construction of access roads to the installation sites. In the case of PV installations, this factor, is of particular importance because of the additional need for levelling operations to install the PV modules and avoid slope- and orientation-induced shadows. This has an economic and environmental impact on the project. For this reason, in the proposed method, it was decided to undertake an analysis of the sensitivity of the results to the value established as the limit for the land slope criterion. An analysis was carried out of the repercussions that this criterion has on the land occupancy factor of the PV installations and, consequently, on electrical

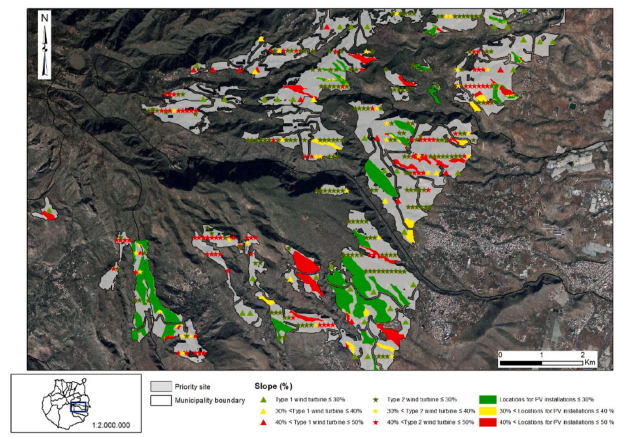

Fig. 11. An example of a map with the results of the analysis of sensitivity to the maximum land slope criterion for a specific part of the priority sites.

energy generation by the renewable installations. Fig. 11 shows the impact on the optimal location for PV installations and the optimal wind turbine distribution of the results of the analysis of sensitivity to the maximum land slope criterion. It can be seen in the figure that as the land slope value falls the useful surface area available for the implementation of PV facilities is considerably reduced, as well as the total installable wind power. If this useful available surface area for each of the land slope criteria is compared with the gross initial surface area of the priority sites priority sites [36] the value is obtained for the land occupancy factor. Table 2 compare the results obtained when the land slope is ≤ 50 % with those in which the constraint value is 40 % and 30 %. It can be seen that variation in the maximum slope criterion has a significant impact on the PV installation land occupancy factor, ranging from 15.9 % in the case of a slope constraint value of ≤50 %–10.8 % for a value of ≤30 %.

This sensitivity has significant repercussions on the amount of renewable energy capacity (see Table 3). Based on the installable power for each case, and following an analogous procedure to that described in subsection 3.3, calculation can be made of the renewable energy

Table 2
Sensitivity of PV installation land occupancy factor to the established maximum slope value.

PV installation land occupancy factor		
Land slope ≤50 %	Land slope ≤40 %	Land slope ≤30 %)
15.9 %	12.8 %	10.8 %

Table 3
Sensitivity of renewable energy capacity for self-consumption to the established maximum slope value (in MW).

Municipality Id.	Land slope ≤50 %)		Land slope ≤40 %		land slope ≤30 %	
	Wind power	PV power	Wind power	PV power	Wind power	PV power
1	29.3	9.4	26.20	8.23	20.00	8.23
2	94.4	214.9	87.30	164.04	77.80	152.67
3	19.3	9.7	12.30	7.32	6.90	3.81
4	83.6	72.2	68.80	66.83	54.20	49.94
5	109.2	64.3	87.90	48.85	71.40	34.33
6	0	12.7	0.00	12.75	0.00	10.59
7	32.2	91.1	29.90	87.17	25.30	78.96
8	0	3.9	0.00	3.90	0.00	2.50
9	21.8	40	19.40	31.12	13.20	28.37
10	11.5	7	9.20	5.97	9.20	4.13
11	143	66.4	2.30	8.46	0.00	8.46
12	2.3	8.5	117.20	41.32	105.40	29.60

generated in self-consumption regime and the degree of demand coverage for each municipality and for each of the maximum slope values established (see Table 4). It can be seen, by way of example, that the municipality of Artenara (Id. = 3), whose orography varies considerably, experiences a 65.1 % reduction in the degree of coverage, while municipalities with a coverage rate close to 1 (Id. = 9,10,12) see reductions of up to 33.6 % when comparing the slope constraint value of ≤50 % with that of ≤30 %. The importance can therefore be deduced of undertaking a detailed analysis of the technical characteristics of the orography of the land in order to be able to more precisely define the renewable power capacity and optimize its exploitability. This aspect is potentially even more important in countries/regions where land availability for this type of installation is limited.

3.5. Economic and environmental benefit results

To calculate the specific cost of electrical energy generation through the renewable installations, Eq. (4) was used:

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX}\cdot\mathrm{CRF} + \mathrm{C}_{\mathrm{O\&M}}}{ECF} \tag{4}$$

where LCOE is the levelized cost of electricity, CAPEX is the initial investment cost (€/MW), CRF is the capital recovery factor (see Eq. (5)), $C_{O\&M}$ are the annual operating and maintenance costs of the installation (in €/MW/year), and *ECF* is the equivalent capacity factor.

$$\mathrm{CRF} = \frac{\mathrm{r}(1+\mathrm{r})^{\mathrm{Lt}}}{(1+\mathrm{r})^{\mathrm{Lt}} - 1} \tag{5}$$

where r is the discount rate (taking a value of 3 %, which is considered normal in stable macroeconomic circumstances for the study area), and Lt is the technical lifetime of the installation (in years).

For the study undertaken in this paper, the most appropriate mean CAPEX and $C_{o\&M}$ values, for both the PV and wind installations, were taken from Ref. [45] considering those offered in that document for countries/regions determined to be equivalent to the area of the case study. For the case of wind installations, the values are 1100€/kW and 41.0€/(kW.year), for CAPEX and Co&M, respectively. For PV installations, the corresponding values are 876€/kW and 13.20€/(kW.year), respectively.

To calculate the CRF (Eq. (5)), the wind and PV installations were assumed to have useful lives of 20 and 25 years, respectively. Different CRF values were therefore obtained depending on the type of renewable installation. In addition, given that the ECF differs depending on the municipality where the renewable installation is located, through Eq. (4) the LCOE value is differentiated by municipality and type of renewable installation. Finally, taking into consideration the proportion of energy that each renewable source contributes in each municipality, an equivalent renewable LCOE value ($LCOE_{eq}$) was calculated for each municipality (Table 5).

As previously mentioned, the case study is an island territory with an isolated electricity system, not interconnected with any other territory and with very high specific electricity generation costs. This is due, on the one hand, to the additional cost derived from not being able to take advantage of the advantages implicit in economies of scale and, on the other hand, as the case study is an island electricity system where generation depends on limited demand, the capacity factors of the current conventional generation equipment are considerably lower than standard ones. The average specific cost of electricity generation on the island of Gran Canaria in 2021, which is the most recent year with official published data from the Canary Government, was 0.1615 €/kWh [34]. This is considerably higher than the average cost when considering the entire Spanish territory. The difference in cost due to the island nature of the Canary Archipelago is borne by Spain's electricity system operator.

If we compare the current average specific cost of electricity generation and the costs of generation through renewable installations in a self-consumption regime, we can estimate the specific economic savings that could be achieved. With this data, and taking into account the total energy that can be supplied in a self-consumption regime by renewable energies (Table 1), we calculated the total economic savings for each municipality (Table 4).

According to the latest official data from the Canary Government, the equivalent specific emission of the island's electricity generation system is 0.67tCO_2/MWh [34]. Based on this datum, and the energy that could be provided by the renewable installations under the self-consumption regime, we calculated the tCO^2 that it would be possible to avoid emitting into the atmosphere in each municipality (Table 4).

It is concluded that, for the case study, the strategy proposed through

Table 4
Sensitivity of energy demand coverage to the established maximum slope value.

Municipality Id.	Electrical energy demand coverage (Available renewable energy for self-consumption/Energy demand)		
	Land slope ≤50 %	Land slope ≤40 %	Land slope ≤30 %
1	8.05	7.14	5.63
2	2.00	1.66	1.52
3	45.27	29.34	15.80
4	4.74	4.08	3.15
5	7.53	5.97	4.72
6	0.02	0.02	0.02
7	0.47	0.45	0.40
8	0.19	0.19	0.12
9	1.04	0.86	0.69
10	1.07	0.88	0.80
11	1.71	1.32	1.14
12	1.04	1.04	0.75

Table 5
Economic and environmental benefit results.

Municipality Id.	$LCOE_{eq}$ (€/kWh)	Economic saving for the electrical system (M€/year)	tCO_2/year avoided
1	0.0357	1.77	9398.7
2	0.0337	46.63	244,450.0
3	0.0374	0.21	1123.2
4	0.0358	10.63	56,650.3
5	0.0322	8.87	45,950.1
6	0.0362	3.72	19,884.1
7	0.0354	33.75	179,390.6
8	0.0385	1.64	8921.2
9	0.0351	17.46	92,561.8
10	0.0383	5.31	28,883.6
11	0.0357	42.31	225,371.7
12	0.0386	2.65	14,418.5

the method proposed in this paper could lead to a total economic saving for the Spanish electricity system of 174.93 M€/year and would avoid emitting 927ktCO_2/year into the atmosphere.

4. Conclusions

This paper proposes a method that uses GIS techniques to evaluate the capacity of medium-large scale wind and solar PV energy use and was applied to a case study on an island. As a novelty, the method is particularised for medium-large scale renewable installations for energy self-consumption, thus enhancing distributed electricity generation through energy communities and, in its implementation, topographic (e.g. slope, orientation and shading), energy (e.g. capacity factor) and logistical (road network, etc.) factors were jointly considered.

The results obtained in the case study show the major importance of considering the technical characteristics of the topography of the terrain in demarcation of the useful area for the implementation of PV installations and in the distribution of wind turbines. This is a key factor for an accurate assessment of the renewable power that can be installed and for optimising the energy yield of these installations.

For the case study conducted in this paper, the resulting land occupancy factor for PV installations, in relation to the gross available area, was 15.9 %. This value is markedly different from the values that have been arbitrarily adopted in previous studies. The electricity generation capacity of the renewable energy installations for self-consumption exceeded 100 % of the demand in 9 of the 12 municipalities analysed.

In addition, a study was carried out on the sensitivity of renewable energy use for self-consumption to the maximum value adopted for the slope of the land, as this is one of the topographical characteristics considered to be key. In the case study, the maximum slope was limited to 50 %. However, when the slope was limited to 40 % and 30 %, the resulting land occupancy factor was significantly reduced to 12.8 % and 10.8 %, respectively, with a consequent loss of useable renewable energy capacity.

This proposed method is key in the energy planning of regions and/or countries. It is perhaps more relevant in territorial contexts where the availability of land is limited and so more precise and detailed analyses are required to identify optimal locations for renewable energy facilities for self-consumption, all within the framework of policies aimed at optimising land use and management. The promotion of this type of installation for self-consumption and, consequently, of distributed electricity generation, favours the quality and stability of the electricity supply, especially in electricity systems that are not very robust.

CRediT authorship contribution statement

Francisco Santana-Sarmiento: Writing – original draft, Software, Methodology, Investigation, Data curation. **Sergio Velázquez-Medina:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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