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ScienceDirect
Renewable Energy 33 (2008) 545–552
RENEWABLE ENERGY
www.elsevier.com/locate/renene

Review

The electricity production capacity of photovoltaic power plants and the selection of solar energy sites in Andalusia (Spain)

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Received 8 November 2006; accepted 22 May 2007
Available online 12 July 2007

Abstract

The privileged climate and orographic setting of southern Spain give Andalusia an enormous potential for the installation of photovoltaic power plants connected to electricity grids and also for individual use. These circumstances as well as the present energy crisis, largely stemming from the world's dependence on fossil fuels, justify this research study. This article describes how the GIS was used to inventory the most suitable land sites for the location of solar power plants for the production of electrical energy in compliance with the legal, environmental, and operational requisites for grid-connected photovoltaic power plants (GPPPs). On the basis of this inventory and the calculation of the global irradiation on horizontal surface, it is estimated that the electrical production capacity of GPPPs in Andalusia doubles the Special Regime electricity demand. The resulting electricity production capacity is estimated at 38,693 GWh/yr for 164,495.37 ha of land, which has no legal and/or environmental impediments to solar power installations.

Keywords: Renewable systems; Photovoltaic energy; Environmental issues; Andalusia; GIS

Contents

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doi:10.1016/j.renene.2007.05.041

1. Introduction

The unsustainability of the present production–consumption energy model highlights the finite nature of conventional energy resources as well as the environmental degradation necessarily resulting from such a model [1]. Energy consumption in developed countries has a growth rate of approximately 1% per year, and that of developing countries, 5% per year [2]. Present oil and natural gas reserves can only cover this rate of energy consumption for the next 40 years in the case of oil, and for the next 60 in the case of natural gas.

The Kyoto Protocol is part of the United Nations Framework Convention on Climate Change. Its main objective is to extract a firm commitment from developed countries to reduce their greenhouse gas emissions [3,4]. The increased use and advancement of renewable energy technologies (solar thermal, biomass, wind, and hydroelectricity) seem to be a viable solution for environmental problems produced by other energy sources. For this reason, current policies focus on fomenting the development and use of renewable energy in Europe.

The high level of insolation in the region of Andalusia (Spain), the presence of the Almería Solar Platform, the largest solar energy research and development station in Europe, as well as various projects financed and developed by private industry are all factors that will undoubtedly give Andalusia plays an important role in the implementation of renewable energy technology in Europe. This region has the capacity to provide sufficient energy for its needs, and can even contemplate the possibility of exporting such projects to other countries. The population distribution in Andalusia shows that there is a great potential market for renewable energies, among which solar energy should be highlighted because of its homogeneous presence throughout the entire region [5].

In Spain, the *Plan to Encourage the Use of Renewable Energies* [6] has the same objective as the European Union in its *White Paper on Renewable Energies*, which states that at least 12% of the total energy demand in Spain should be covered by renewable energy sources.

In this same line, one of the main objectives of the Energy Plan for Andalusia 2003[1] [7] is the development of this type of energy. More specifically, this document lays the groundwork so that in 2010, 15% of the total energy demand in the region will be provided by renewable energy sources. By 2006, a significant part of this total (10.6%) should already be attained.

However, if we compare the use of renewable energy (primary as well as final power sources) in Andalusia to their use in the rest of Europe, it is obvious that at the moment they provide only a small percentage of the general energy supply. In Spain, as a whole, renewable energy represents only 6.7% of the primary energy consumption. However, this percentage is higher than the percentages in both Europe (6.0%) and Andalusia (5.6%).

The *Real Decreto*[2] 436/2004 [8], a national law passed in 2004, contains measures which transform the installation of grid-connected photovoltaic power plants (GPPP) into a lucrative investment, despite the fact that non-refundable loans for this type of installation are no longer available in Andalusia.

Article 33 of this same law regulates the rates, bonuses, and incentives given for solar energy installations (category b, group b.1). It specifies a new power limit per installation of 100 kW so that the kWh produced can be sold to the utility provider at a rate of 575% of the internal rate of return for the first 25 years after it begins to operate, and at a rate of 465% during the years afterwards. Considering actual market prices, and depending on installation costs and electricity production capacity, the recovery of an investment in a GGGP of 100 kWp takes approximately 10 years [9].

As a result, investors often consider the possibility of investing in installations of less than 100 kW, or in "solar farms" (arrays of photovoltaic installations in the same area, but with a variety of owners) as a retirement plan. Once the investment recovery period is over, the GGGP becomes a business with a useful life of more than 40 years and with an internal rate of return of more than 10%.

In recent years, the lack of water for existing hydroelectric power plants, administrative obstacles, such as delays in granting licenses and concessions, and finally, environmental considerations [10] has signified that existing thermal power plants have had to operate at a higher production level. This has evidently increased contamination. The result is that in 2005, the 73 plants registered as large-scale combustion facilities emitted 288,117 tons of nitrogen oxides.

As a consequence of the previously mentioned legislation, as well as the favorable climate conditions, a significant number of GGGPs are presently in the design phase. However, the engineers do not have reliable information regarding local climate conditions or geography, which would enable them to select the optimal location for such installations.

The information presently available is much too general. For example, the *Conserjería de de Agricultura y Pesca*[3] of the Andalusian Regional Government has a mere 60 measuring stations, and the *Instituto Nacional de Meteorología*[4] only has six stations capable of measuring global irradiance.

Certain authors [5,11,12] have calculated the levels of solar radiation in Andalusia and Spain. For this purpose, they have generated maps by means of different techniques

[1] *Plan Energético de Andalucía* 2003 (PLEAN).

[2] A national law in Spain is known as a royal decree [*Real Decreto* (*R.D.*)].

[3] Andalusian Regional Office of Agriculture and Fishing.

[4] National Meteorological Institute of Spain.

by analyzing data provided by the *Conserjeria de Agricultura y Pesca*, collected from its measuring stations, or the multi-layer perceptron system.

In addition, there are other systems or models that can be used to estimate solar radiation [13,14], which have more data distributed for a wider range of latitudes. This led us to the conclusion that the correlation coefficients proposed in other studies should be revised and compared with a view to evaluating and proposing a new set of regional coefficients.

More recently, due to the scarcity of measuring stations and the high cost of obtaining data from other more sophisticated types of system, scientists have begun to evaluate solar radiation on the basis of satellite images [15]. This method is the one recommended by the World Meteorological Organization for the evaluation of the spatial distribution of solar radiation.

This research study estimates the potential for the use of GGGPs in Andalusia, based on the optimal levels of solar radiation, ESH (equivalent sun hours per year in kW/kWp) and on the inventory of the most suitable best land sites for the location of GGGPs.

2. Materials and methods

2.1. Global solar irradiation

The information regarding total global solar irradiation on horizontal surface and average annual temperatures, as well as the calculation algorithms used to estimate electricity production have been obtained from the European Project PVGIS [16]. This project is based on the geographic information systems expressly applied to radiation values. A geographic information system (GIS) can be defined as an ‘‘integrated collection of computer software and data used to view and manage geographic data, analyze spatial relationships, and model spatial processes’’.[5] This GIS is part of the project SOLAREC that has been sponsored by the European Union through the JRC (Joint Research Centre, reference point for science and technology in the European Union).

The solar radiation database contains homogenized climate data for Europe, which is available in the *European Solar Radiation Atlas*, using the r.sun model and the interpolation techniques, s.vol.rst and s.surf.rst. The model algorithm estimates beam, diffuse and reflected components of the clear-sky and real-sky global irradiation on horizontal or sloping surfaces. For each time step during the day, the calculations account for sky obstruction (shadowing) by local terrain features (hills or mountains). In this way, we have generated a map of total horizontal solar irradiance, which includes accurate data regarding the average temperatures in 205 municipalities.

[5] *GIS Dictionary* (http://support.esri.com/index.cfm?fa = knowledgebase.gisDictionary.search&searchTerm = GIS).

2.2. Location of GGGPs

One of the principal objectives of our study is the determination of the most optimal sites for the location of GGGPs. This land has been chosen according to the criteria in Table 1, and is principally based on the minimization of the possible environmental impact derived from the construction and actual launching of future photovoltaic power plants.

To discover the exact location, surface, and scope of influence of these discrimination factors, we used the databases and official publications of the Andalusian Regional Government as well as maps of our own authorship. This information enabled us to make an inventory of all land in Andalusia with little or no agricultural and environmental value. This land was judged to be the optimal location for GGGP sites.

Evidently, the maps that we created will be very useful for GGGP designers since they constitute an important resource, which will greatly simplify the work of photovoltaic technology technicians and users. The data obtained for our study has been generated with a GIS by means of the Arcview 3.2 computer application. This tool allows the information to be processed and represented along with other data that will be added in the near future. A much better performance is thus obtained than when such information is considered in isolation [17,18].

In order to achieve greater data homogeneity, we have studied 205 municipalities throughout Andalusia, the majority of which have more than 5000 inhabitants (see Fig. 1). Since the ideal model is estimated to be a ‘‘distributed generation’’ model, another requisite for optimal GGGP sites is their proximity to an urban nucleus, and thus, to areas where consumer goods are bought and sold.

As a starting point, we defined a circular area around each municipality, situated at a distance and width of 4 km from the outer limits of the city center to the circumference of the circle. Such measurements allow for future urban growth and minimize losses in the transport of the electrical energy generated. In this way, we have obtained an initial surface area of 2,485,810.67 ha, as possibly suitable for GGGP locations. We have analyzed this surface area by applying the discrimination factors described in the previous section. The results of this process give the net area of land with little environmental value, and where a solar energy installation would have zero environmental impact (Fig. 1).

In our opinion, the results obtained show the most suitable land sites for the installation of GGGPs because of their low environmental value and excellent conditions in a distributed generation system. However, it is only fair to mention that these are not the only geographic locations possible since there are other sites outside the designated areas, which, to a greater or lesser degree, also comply with the requisites for solar energy plants. Nevertheless, the vastness of the geographical area under study obliges us to

Table 1
Discrimination factors for selection GGGP sites in Andalusia

Criteria for land selection			
Environmental	Legal	Orographic	Climatological
National parks Nature parks Areas of community interest Bird sanctuary Natural cattle trails Livestock paths Land uses	Complaints roads Complaints rivers Complaints coastlines Complaints patrimony Cultural heritage Urban planning	Slope >2% Shadows Accesses Proximity to consumer areas	Levels of global irradiance Annual equivalent sun hours Temperatures

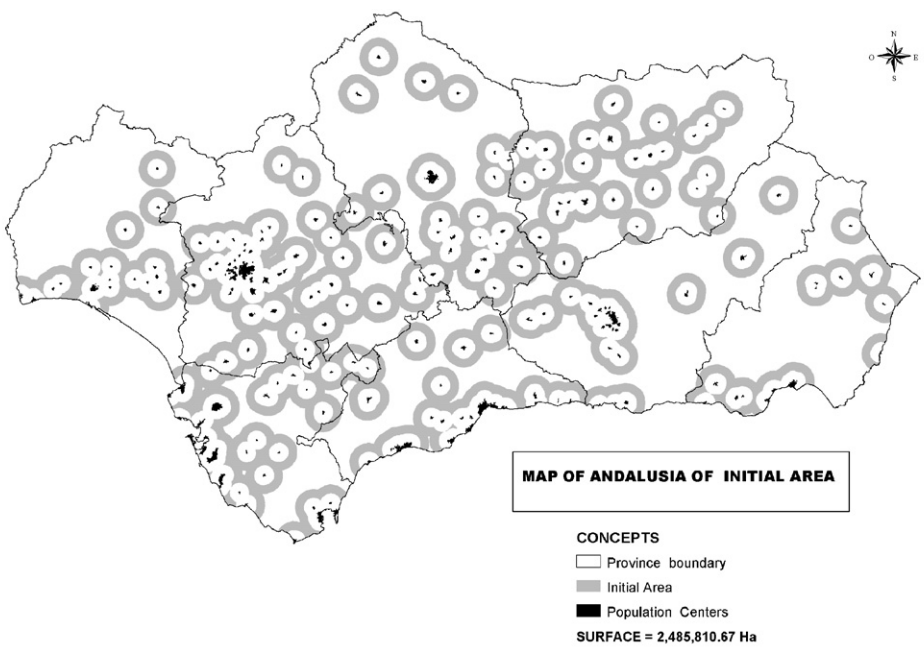

Fig. 1. Map used for the initial study of optimal land sites in Andalusia by means of the distributed generation system.

restrict our proposal only to the most optimal locations. Similarly, our study does not take into account the possible use of photovoltaic systems in the building sector. Nevertheless, given the importance that this issue is presently acquiring in Spain, thanks to recent legislation [19], it may be included in research studies that we will carry out in the future.

3. Discussion of results

3.1. Determination of the most suitable terrains for the location of GGGPs

An extremely important factor in our selection of locations was slope angle. All land sites with a slope greater than 2% was eliminated since this type of slope signifies that the first row of solar panels, unless they happen to be facing the south, would throw shadows on the panels in the row behind them, thus decreasing the performance level of the solar energy plant.

Another important factor was the protected spaces such as Nature Parks, National Parks, Areas of Community Interest, and bird sanctuaries, as well as other legal factors such as the existence of natural historic cattle trails, roads, public channels, police areas, etc.

Logically, another requirement for our selection was that the land should be of low agricultural value. Accordingly, all land with irrigation systems, fruit trees, olive trees, forests, bushes, etc., was rejected. The land selected is mostly abandoned, not apt for crops or with scattered areas of dryland crops and crops under plastic.

The result obtained (see Fig. 2) is the net extension of land that complies with all of the initial requirements for the location of GGGPs. The total land surface comes to 164,495.37 ha, 128,270.05 of which have sparse dryland vegetation and is mainly located in the province of Seville, followed by Cadiz and Cordoba. The rest of the

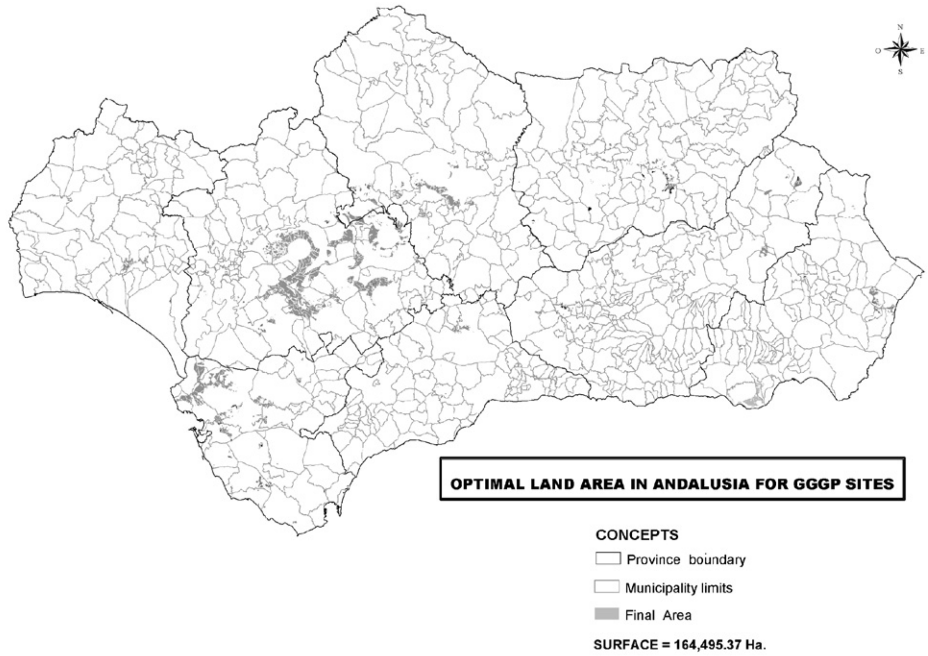

Fig. 2. Net land surface obtained.

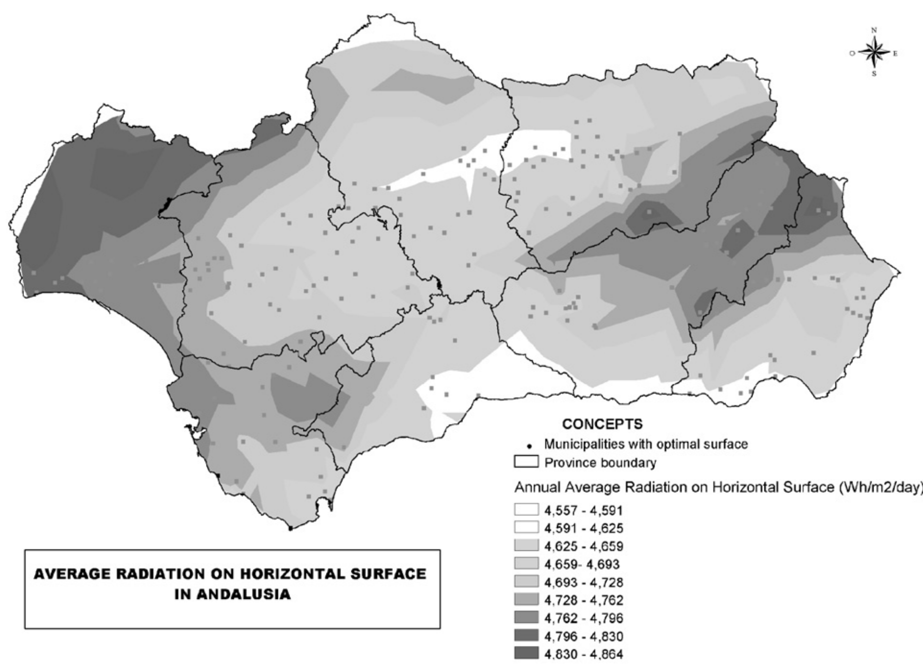

Fig. 3. Map of average radiation on horizontal surface in Andalusia.

land has different types of vegetation and crops under plastic.

3.2. Determination of global irradiation levels on horizontal surface

Regarding global irradiance levels on horizontal surfaces, the results of our study show higher levels in the northeastern section of the province of Granada (also known as the *Altiplano* because it is a high plateau) and neighboring areas of the provinces of Almeria and Jaen as well as certain coastal municipalities in Huelva and Cadiz (see Fig. 3).

The irradiance data obtained varies between a maximum value of 1801 kWh/m^2/yr, and a minimum of 1652 kWh/m^2/yr with an average value of 1713 kWh/m^2/yr for radiations on horizontal surface. In the case of the irradiance on an optimal sloping surface, the values increase by approximately 10%, achieving a maximum of 2034 kWh/m^2/yr, a minimum of 1864 kWh/m^2/yr, and an

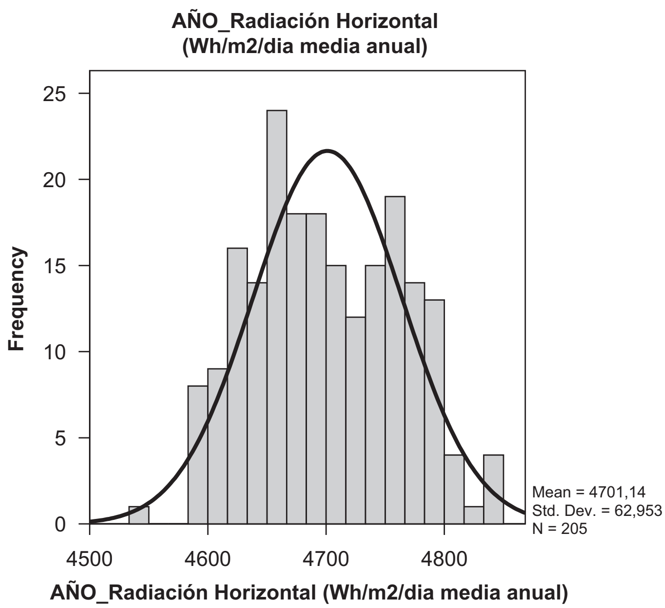

Fig. 4. Histogram of annual average global irradiation values on horizontal surface.

average of 1938 kWh/m^2/yr. The irradiance values obtained on a vertical surface show a maximum value of 1286 kWh/m^2/yr, a minimum of 1140 kWh/m^2/yr, and an average value of 1219 kWh/m^2/yr.

The level of solar radiation is evidently a determining factor in the study of the solar energy potential of a region. It is interesting to compare the values obtained in this study with those obtained in Ridao et al. [5], based on information from 68 measuring stations throughout Andalusia, in which the average solar radiation was found to be 4.55 ± 0.33 kWh/m^2/day. In this study (see Fig. 4), the average solar radiation value obtained is 4.7 ± 0.06 kWh/m^2/day. This signifies a difference of approximately 3% over the value obtained in the initial study.

In Ridao et al. [5], important seasonal differences were observed. The average maximum values obtained for the summer months were 6.44 ± 0.55 kWh/m^2/day and average minimum values in autumn were 2.89 ± 0.25 kWh/m^2/day. The values obtained in the study described in this article reflect maximum and minimum values of 7.21 ± 0.32 kWh/m^2/day and 3.83 ± 0.21 kWh/m^2/day for summer and autumn, respectively. Even when monthly series are compared, the differences between the results vary between 10% and 23% for monthly values. This signifies that despite the different methods followed, the results regarding global irradation levels on horizontal surface are very similar in both studies.

3.3. Average temperatures

We have considered it interesting to include the average temperature values for the areas studied, given the negative effect of the temperature on the performance and production capacity of silicium cells.

We have analyzed possible GGGP sites not only according to their global irradation levels on horizontal surface, but also according to their average annual temperature. The reason for this is that such sites should have high radiation levels as well as moderate or even low average temperatures. The importance of the temperature is evident in the equation of the maximum power point of a photovoltaic generator [20]

$$P_{\mathrm{m}} = P_{\mathrm{m}}^{*} \times \frac{G}{G^{*}}[1 - \delta(T_{\mathrm{c}} - T_{\mathrm{c}}^{*})], \tag{1}$$

where

$$T_{\mathrm{c}} = T_{\mathrm{a}} + \left[\frac{\mathrm{TONC} - 20}{800}\right] G, \tag{2}$$

where G is the global incident irradiance on the surface of the photovoltaic module; T_{c} the temperature of the cell; T_{c}^{*} the temperature of the cell at standard conditions; T_{a} the normal room temperature; P_{m} the maximum power point of the photovoltaic generator; P_{m}^{*} the nominal power at standard conditions, STC; TONC, the nominal operating temperature; and δ the variation coefficient with the temperature of the power, given by the following equation [21]:

$$\delta = \frac{1}{qV_{\mathrm{m}}}\left(\frac{qV_{\mathrm{m}} - E_{\mathrm{g}}}{T} - \gamma mk\right), \tag{3}$$

where E_{g} is the GAP energy and m is the diode ideality factor in the equation representing the curve I–V.

As previously mentioned, temperature plays an important role in the production capacity of photovoltaic systems. For this reason, areas with lower average temperature values are more optimal since this feature enhances system performance. Fig. 5 shows that the highest temperatures occur in the central and western area of Andalusia, which, curiously enough, is where the land is the flattest. It thus has the most suitable profile for a GGGP site.

3.4. Electricity production capacity of GGGPs

The potential for electricity generation has been calculated on the basis of the horizontal irradiation and assuming its incidence on optimal sloping surfaces. To find the total electricity generated by a photovoltaic system E (kWh), the following equation has been used [16]:

$$E = 365 \otimes P_{\mathrm{k}} \otimes r_{\mathrm{p}} \otimes G, \tag{4}$$

where P_{k} (in kW) is the maximum power installed; r_{p} the efficiency of the system (or performance ratio) (the typical value in this case is 0.78 for monocrystal or polycrystal silicium.); and G the average annual value for total daily global irradation on the horizontal or sloping surface of the module.

Fig. 6 thus shows the electricity production capacity in MWh for a permanent, fixed installation without solar tracking. On the basis of the available useful surface in

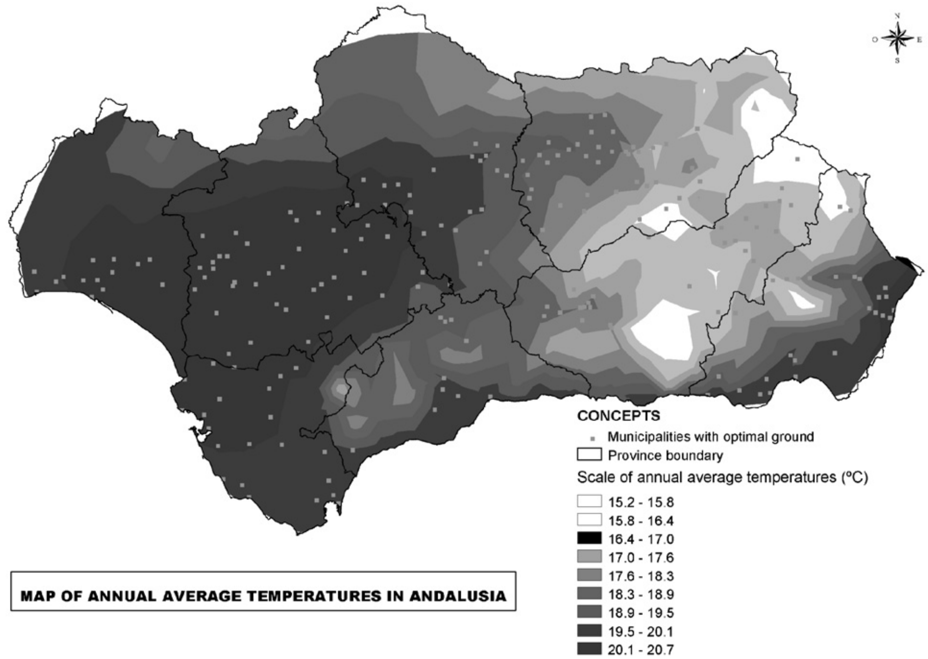

Fig. 5. Map of annual average temperature in municipalities in Andalusia.

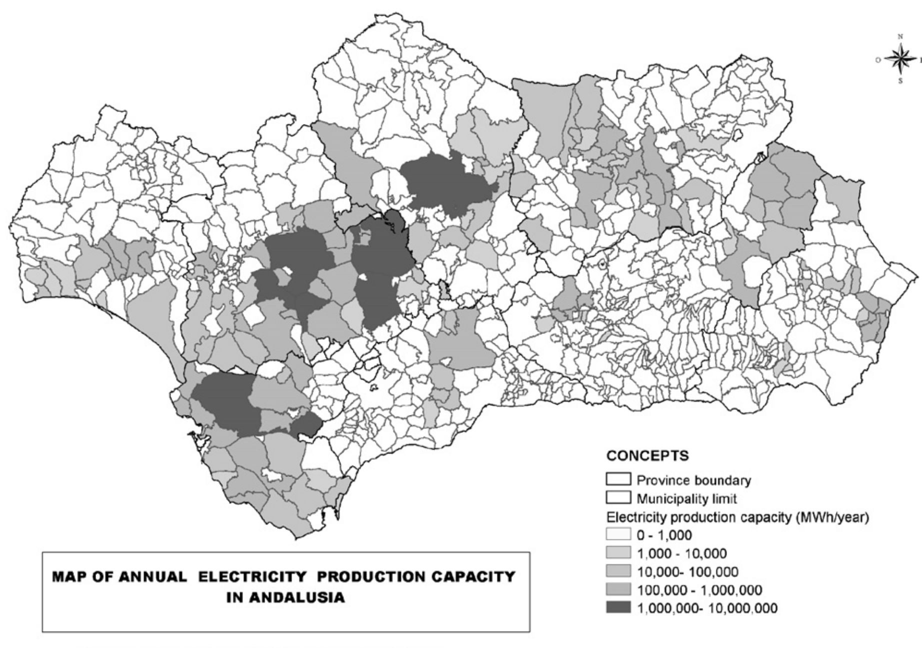

Fig. 6. Map of the annual electricity production capacity for photovoltaic systems in Andalusia.

each area and the ground necessary for each kWp, the estimate comes to approximately $60\,m^2$.[6] It is then relatively simple to estimate the absolute electricity production capacity in kWh or in multiples of the same. Consequently, the new quantity obtained is the annual electricity production capacity for GGGPs that would occupy the useful ground surface that was determined in Fig. 2.

With the result of 38,693 GWh/yr shown on the map (see Fig. 6), and the data on electrical energy consumption in Spain and, more specifically, in Andalusia for 2003 (Table 2[7]), it is evident that there is sufficient capacity in Andalusia to cover an energy demand of 33,255 GWh/yr that the region needed in 2003.

[6] This surface takes into account the ground for transit areas within the photovoltaic power plants, the land surface necessary for the location medium and low-voltage installations and the separation between rows.

[7] *Comisión Nacional de la Energía* [22].

Table 2
Electrical energy consumption in Spain 2003 (GWh)

Type	Andalusia	Spain
Hydraulic	1297	38,773
Nuclear	–	61,875
Coal	13,811	72,249
Fuel oil/gas	1286	8035
Combined cycle	3673	14,990
Gross production	20,067	195,922
Generation	−732	−8061
Pumping	−760	−4678
Net production	18,575	183,183
Special regime	5242	39,762
Total	23,817	222,945
Interchanges	9438	1263
Gross demand	33,255	224,208

The analysis of data in this study shows that it is increasingly necessary to think about replacing the energy generated by thermal power plants (e.g. coal, fuel oil/gas and combined cycle) with energy from sustainable energy sources. According to this research study, this signifies that energy needs with Special Regime GGGPs would only be 18,770 GWh/yr, half of the production capacity of Andalusia.

4. Conclusions

Our study shows that with the 164,495.37 ha of land resulting from the site selection process carried out, Andalusia has more than sufficient land surface for the location of GGGPs with sufficient power generation capacity to replace the thermal power centers presently in operation. The land selected is optimal because it is not vulnerable to environmental impact. The selection process prioritized that part of Andalusia that fulfils all the requirements for the construction and operation of solar power installations.

Similarly, our study also shows that Andalusia has a suitable climate for the installation of photovoltaic power plants because of its high levels of solar radiation and its moderate temperatures. With the resulting potential electricity production capacity of 38,693 GWh/yr by GGGPs, there are sufficient resources available to replace fossil fuel thermal power installations with solar power plants that use renewable energies for the production of electricity.

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