Photovoltaic Techno-Economical Potential on Roofs in the Canary Islands

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ABSTRACT

The Canary Islands (Spain) are highly dependent on imported oil. For 2015, the Energy Plan has established that 30% of the electricity demand will be covered by renewable energy sources, mainly wind and solar. One limitation in the Archipelago is the lack of available land. Considering both issues, land scarcity and energy goals, it is crucial to determine the photovoltaic (PV) potential on roofs. In this article, a methodology to determine the roof PV potential for small regions and/or islands is applied to the case of the Canary Islands. The results show that the potential PV production is higher than the electricity demand at competitive prices. Different scenarios depending on the use of the available roof area, economic assessment based on cost-resource curves and comparison of daily and monthly profiles (PV production versus electricity demand) have also been studied.

KEYWORDS

Renewable energy resources, Canary Islands, Solar photovoltaic potential, Building roofs

INTRODUCTION

The Canary Islands is a Spanish Archipelago located in the northeast Atlantic, in front of the Western coast of Africa (parallel 28). It comprises seven islands with a total surface of 7490 km^2 and over two million inhabitants. The tourism sector is the main economic activity, moving over 12 million visitors last year (2012) [1].

The Archipelago is highly dependent on external energy sources. Nearly 98% of the primary energy consumption is based on imported oil brought to the islands by ships. Speaking about electricity, this percentage reached 93% in 2012 [2]. The Canary Islands have no conventional energy sources, but they have plenty of renewable energy resources, mainly wind and solar.

For these islands it is of high importance to increase the level of energy self-sufficiency. This can only be done by deploying renewable energy sources (RES). RES are autochthonous energy sources that contribute to reduce the energy dependency and to diversify the energy sources. The deployment of RES contributes also to foster employment and to encourage regional development.

The electrical power installed in the Canary Islands in 2011 was 3,138 MW; renewable energies came up to 9% of the total installed power but, in terms of production, this percentage represented ca. 7% [22]. The RES from wind and solar photovoltaic are 145 MW and 129 MW respectively in 2011 [22]. Most of the PV power is installed on land (PV farms) and only a minor part on buildings.

For 2015, the Canary Islands Energy Plan has established that 30% of the electricity generation should be supplied by RES, mainly wind and solar. This plan requires that wind energy has to reach 1,025 MW, photovoltaic 160 MW and wave energy 50 MW [3].

On the other hand, available land is scarce in the Archipelago. Over 40% of the total surface of the archipelago is protected. The average population density is 283 pop/km² (570 pop/km^2 discounting protected areas), increasing severely around coastal areas and major cities (close to 4,000 persons/km²) [1].

Taking this context into account, it is understandable that land availability is an issue on the islands. There is a strong territorial pressure on the islands, finding available land for PV purposes is difficult since it competes with urban, rural and tourist developments and, when this is not the case, very often the natural environment wants to be preserved and, usually, no license is granted to build up PV farms.

Considering both issues, land scarcity and energy goals, it is crucial to determine the PV potential on roofs for each island as a first step for energy planning. Another advantage of building integrated PV systems is that it enables electricity production and consumption at the same site, avoiding losses in electricity distribution.

For small regions or islands, the literature review did not provide accurate and inexpensive methods that could be applied for obtaining reasonable results. Very often the scale considered in the articles was too large: continents [4-7], countries [8-10] or large regions [10-12]; or too small: cities [13] or urban areas [14-21]. This is why a methodology was developed to estimate the PV potential on roofs in territories like small regions or islands. This methodology is broadly explained in [22]. In this paper, the methodology developed in [22] is applied to the case study of the Canary Islands and the results are discussed.

The Canary Islands are seven islands exhibiting different characteristics, see Table 1, [1].

Table 1. Indicators per island, [1]

	Gran Canaria	Lanzarote	Fuerteventura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
Island surface, [km^2]	1560	846	1660	2034	708	370	269	7447
Population	852,225	142,132	106,456	898,680	85,468	22,350	11,033	2,118,334
Tourists number per year	3,311,695	2,075,537	1,918,317	4,406,470	127,023	42,405	27,788	11,909,235
Tourists per year vs. population	389%	490%	1802%	1460%	149%	190%	252%	562%
Average stay, [days]	9.4	8.86	9.77	9.55	10.4	4.0	2.8	9.4
Average number of tourists per day	85,378	50,387	51,353	115,305	3,623	468	216	306,730
Tourists vs. population	10%	35.5%	48.2%	12.8%	4.2%	2.1%	1.9%	14.5%

These different characteristics influence the results obtained in the different islands. One of the aims of this paper is to discuss the results as a function of the island characteristics. The Canary Islands is one region that includes two different provinces. Tenerife and Gran Canaria are the so-called "capital islands", since each of these two islands is the capital of one of the provinces. The whole regional government and administration is located in these two islands. These two islands together comprise more than 80% of the total population, exhibiting also the highest population density. Main services and industry are also concentrated in these two islands. Although all islands are tourist, the so-called "tourist islands" within this article are Fuerteventura and Lanzarote, because their main activity is tourism, exhibiting the highest ratios of number of tourists versus population, representing from 35% to ca. 50% of the average population on a daily basis (see Table 1). The tourist sector in these islands is mainly "sun and beach" tourism. The remaining three islands, La Palma, La Gomera and El Hierro, are the smallest, less populated, less tourist and greener islands. These islands are called in this study as "rural islands".

METHODOLOGY

Introduction

The methodology adopted to assess the PV potential on roofs depends mainly on two different criteria:

- Scale of the target region;
- Data that are available.

Therefore, scale and available data determine which method should be used.

Scale of the target region. Very often the same techniques cannot be applied at local, regional or continental scale [10]. For instance, it may be possible to quantify shadow effects among buildings in a city using digital three-dimensional models [23] but this is not a practical option when the scope of the study is a whole continent. For similar reasons, average data are usually considered a first approach [24] for large-scale studies, which is obviously inaccurate but inexpensive.

This is the main reason that led to the development of a methodology adapted to the island dimension, since one of the most important aspects to determine the PV building potential is the size of the area to be studied. This methodology is broadly explained in [22].

Available data. Another important aspect to determine the method to be applied is the type of data that are available. In this case, the most relevant data are the roof surface and the radiation data.

Roof surface – in the literature there are different types of methodologies that can be identified to determine the roof surface. The two most relevant ones are: methods based on the determination of the ratio roof surface per capita and methods based on computing the total roof area of the target region.

Radiation data – the available radiation data make conditional also on the methodology to be implemented. The available radiation data can be point wise data, like data from a pyranometers' network, or continuous data as the ones included in a radiation map. Point wise data are site specific while radiation map provide continuous data for a specific region.

Scale and data: case study

As mentioned in the previous section, data availability and geographical scale make conditional on the methodology selected. The data types utilized in this case study are:

- Scale of the targeted region: the scale is the regional scale. This methodology establishes the PV potential at the municipality level first, then at the island level and finally at the regional level. Therefore, the methodology applied is adequate for the island and regional scale;
- Roof surface data: the method applied is based on computing the total roof area of the target region. This methodology was applied because the surface data of the buildings are available from the Spanish Cadastre;
- Radiation data: for this study particular data from the radiation map have been selected: one mean solar radiation value per municipality, corresponding to the site with the highest population within each municipality, since this is the site where most of the roof surface is also located.

Methodology description

The methodology applied is broadly explained in [22]. Nevertheless, a brief description of the methodology is included in this section.

The methodology used to calculate the PV potential follows three main steps:

- Determination of the available roof area per municipality within each island/region (firstly municipality level and secondly, island level);
- Determination of the annual mean global solar irradiation on optimally tilted plane, per municipality;
- Determination of the yearly PV production per municipality (island and region).

<u>Available roof surface</u>. The assessment of the PV potential on buildings starts with the determination of the total roof surface. Once the total roof area for the target region is calculated, the fractional area available for photovoltaic purposes has to be re-calculated. There are many factors influencing the fraction of available roof area, including shading from other roof parts or neighbouring buildings and trees; use of roof space for other applications, as ventilation, heating/air conditioning, stairwells or chimneys, etc. Such reduction in the available roof area is defined by the so-called utilization factors.

The methodology to calculate the roof area usable for PV purposes follows the next steps.

Step 1: determination of total roof area per municipality. The roof surface data have been processed from the database of the Spanish Land Registry –Spanish Cadastre– (data available at: http://www.sedecatastro.gob.es/).

Step 2: classification of built areas within each municipality. Built areas within each municipality have been classified as: services, industrial, private-residential and tourist.

Step 3: main building and roof types. Buildings can be classified as:

- Industrial buildings;
- Services buildings (e.g. schools, hospitals, commercial areas, etc.);
- Residential buildings, classified in turn, as: high-rise apartment buildings, terraced houses and detached houses.

Roof types identified: flat roof, garret roof and pitched roof.

Step 4: utilization factor per building type. The utilization factors used in this study are summarized in Table 2, [22].

Table 2. Utilization factors per building type, [22]

Building type	Utilization factor	
Industrial	Flat roof	0.9
Services	Flat roof	0.6
Apartment houses	Flat roof	0.43
	Garret roof	0.11
Semidetached houses	Flat roof	0.35
	Pitched roof	0
Detached house	Flat roof	0.48
	Pitched roof	0

Step 5: determination of municipality type. Determination of utilization factors per type of municipality. The residential areas have been classified, depending on the municipality type, as: city, urban, rural or tourist. Service areas (e.g. schools, hospitals, commercial areas, etc.) and industrial areas have mainly the same architectural style independent from the municipality type. But in the residential areas, the architectural style, and therefore the roof availability, depends on the municipality type.

Utilization factors per municipality type are shown in Table 3, [22].

Table 3. Utilization factors per municipality type [22]

Municipality type	Utilization factor
Urban	0.33
Rural	0.32
Tourist	0.32
City	0.35

Step 6: calculation of the available roof area for PV. The calculation of the available roof area for PV purposes per municipality is a function of the municipality type and their utilization factors.

Mean global solar irradiation. The mean global solar irradiation on the horizontal plane, calculated as an annual average, can usually be obtained from radiation maps. One mean solar radiation value per municipality has been selected corresponding to the site with the highest population within each municipality, since this is the site where most of the roof surface is located.

The optimal tilted plane (β_{opt}) has been calculated as a function of the latitude (ϕ) using Equation 1 [25]:

$$\beta_{opt} = 3.7 + 0.69 \times \phi \tag{1}$$

For each municipality, the mean global solar irradiation on the optimal tilted plane has been calculated as a function of the solar radiation on the horizontal plane using Equation 2. See [22] for a discussion of the selected methodology and comparison to other methods.

$$G_{d,a}(\beta_{opt}) = 1.08 \times G_{d,a}(0) \tag{2}$$

Yearly PV production. The yearly PV production per municipality is calculated from the data obtained from the previous two steps, considering two different scenarios:

Scenario 1: the total available roof area is dedicated to PV production.

Scenario 2: the available roof area shares its surface between energy uses (for both solar thermal and PV) and other purposes not related to energy production. The foreseen uses not related to energy are: to hang out clothes and some free-time space (sunbath, barbecue, etc.). The surface foreseen for this purpose is 1 m^2 per person. The surface needed for solar thermal energy has been calculated supposing that a 4 m^2 solar thermal system is capable of providing hot water for one family house (average of 4 persons).

The annual energy PV production has been calculated using equation,

$$E = I_{md} \times 365 \times e \times PR \times A_{PV} \tag{3}$$

where I_{md} is mean daily global radiation on a tilted plane, calculated as an annual average, e is module efficiency (selected module: mono-crystalline modules, η_{MC} = 21.4%), PR is Performance Ratio (*PR* = 0.66), A_{PV} is available area for PV production (after applying utilization factors). See [22] for a discussion of the parameters utilized (*PR* and η_{MC}).

CASE STUDY: METHODOLOGY APPLIED TO THE CANARY ISLANDS

Available roof area

Total roof area. Table 4 shows the total island surface, the total roof surface per island and the percentage of roof area versus total island surface. The total roof surface represents about 1.2% of the total regional surface, but this percentage, as shown in Table 4, varies from island to island. The islands with the highest percentage of built surface are the two capital islands, Gran Canaria and Tenerife, with 2% of its total surface covered by buildings. While, on the other side, the "rural islands", La Palma, La Gomera and El Hierro, exhibit percentages lower than 0.5%.

Table 4. Roof surface per island

	Gran Canaria	Lanzarote	Fuerteve-ntura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
Island surface, [km^2][a]	1,560	846	1,660	2034	708	370	269	7,447
Roof surface, [km^2][b]	30	9	7	37	3	1	0.5	87.5
Roof surface in % vs. island surface	2%	1%	0.5%	2%	0.4%	0.3%	0.2%	1.2%

Source: [a][1]; [b]Spanish Cadastre

Combining roof surface and population data, one can calculate the roof surface per capita, which is, on average, 41 m^2/person. Table 5 shows this ratio per island and the regional average. There is also a difference among the islands: the island that exhibits the lowest ratio is Gran Canaria (one of the capital islands), with only 35 m^2 roof surface per person, and the island with the highest ratio is Fuerteventura (one of the tourist islands), where 65 m^2 roof surface per person are available. The tourist islands, Fuerteventura and Lanzarote, exhibit a higher ratio of roof surface per capita, both over 60 m^2/person. These ratios are coherent, since tourist islands have lower population density than capital islands.

Table 5. Roof-population ratio per island

	Gran Canaria	Lanzarote	Fuertevent-ura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
Roof surface per capita, [m^2/person]	35	61	65	41	38	41	55	41

Built areas per sector. Built areas within each municipality have been classified as: private-residential, tourist, services and industrial. Table 6 shows the percentage of built areas per sector for each of the Canary Islands. Results, as regional average, show that the industrial areas account for about 21% of the total built surface, service areas account for about 18% of the total area, tourist areas for 6.5% and private-residential areas for 54%. Considering the different islands, these percentages change from island to island reflecting the main activity in each island (which is proportional to the built surface within each sector). Thus, capital islands show a higher percentage of industrial areas than other islands. This difference is even bigger when it comes to the tourist areas; for the two main tourist islands, Lanzarote and Fuerteventura, the percentage of tourist surface nearly doubles the percentage in other islands. Also the private-residential percentages exhibit differences among the islands, the rural islands, La Gomera, La Palma and El Hierro, show a higher percentage of residential areas.

Table 6. Percentage of built surface per sector and island

	Gran Canaria	Lanzarote	Fuertev-entura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
Industrial	21%	15%	16%	25%	21%	18%	12%	21.5%
Services	17%	15%	15%	20%	11%	14%	13%	18%
Tourist	7%	11%	14%	4%	3%	6%	0.5%	6.5%
Residential (Private)	55%	59%	55%	51%	65%	62%	74.5%	54%

Main building and roof type. In the Canary Islands, building roofs can be characterized as follows.

Industrial buildings: industrial roofs in the Canary Islands are typically two-sided sloped roof, usually low inclined (around 10º, sometimes higher up to a maximum of 22º) and, sometimes, even flat (0º). *Service buildings* (e.g. schools, hospitals, commercial areas, etc.): usually flat roofs in the Canary Islands.

Apartment buildings: high-rise apartment buildings have mainly two types of roofs, flat roofs or garret roofs.

Terraced houses: terraced houses have mainly flat roofs or peaked roofs (2 or 4 sides).

Detached houses: detached houses roofs have mainly flat or peaked roof (2 or 4 sides).

From these roof types identified in the Canary Islands, the most common one, which can be found in all building types, is the flat roof, which is especially suitable for PV systems.

Table 7, [22] shows the distribution of the different roof types for each residential building type. For the industrial and service buildings the only roof type considered is the flat roof.

Table 7. Roof type distribution, [22]

Building type	Roof type	Distribution
High apartment houses	Flat roof	0.9
	Garret roof	0.1
Townhouse or row	Flat roof	0.7
	Peaked roof	0.3
Detached house	Flat roof	0.7
	Peaked roof	0.3

Municipality type. In the Canary Islands the municipality classification was done based on mainly two criteria: architectonical configuration and population density.

The population density in the Canary Islands is around 280 persons/km^2. This population density varies substantially from municipality to municipality, registering data from 8 to 3731 persons/km^2. Table 8 shows the number of municipalities within each population density interval. 43 municipalities have a population density lower than 200 persons per km^2; 36 municipalities with a population density between 200 and 1000 pop/km^2 and seven municipalities with a population density higher than 1000 pop/km^2. There is also a difference depending on the type of island. In the capital islands the population density is much higher than in the other islands.

Table 8. Population density: number of municipalities within each interval

	Nº of municipalities within each interval							
Population density, [pop/km^2]	Gran Canaria	Lanzarote	Fuertevent-ura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
PD < 50	2	2	3	2	2	3	3	17
50 < PD < 200	6	1	3	7	7	2		26
200 < PD < 500	6	2		12	3	1		23
500 < PD < 1000	5			6	2			13
PD > 1000	3	1		3				7
Average population density, [pop/km^2]	542	167	62	446	123	68	41	283

A study about the population density is advisable before defining the municipality types, since different regions or countries exhibit different average population densities, and what is a low population density for one region may be a high population density in other regions.

Another criterion considered is the roof area per capita. The average ratio for the Canary Islands is 41.3 m^2 roof per person. Table 9 shows the number of municipalities included in the different intervals of roof surface per capita. Three different intervals have been defined: compact municipalities (roof area lower than 25 m^2 per capita), medium municipalities (roof area higher than 25 m^2 but lower than 50 m^2 per capita) and disperse municipalities (roof area higher than 50 m^2 per capita). This table shows that the capital islands have compact municipalities and that the tourist islands have a higher percentage of disperse municipalities than other islands.

Table 9. Roof area per capita: number of municipalities within each interval

Roof area per capita, [m^2/pop]	Nº of municipalities within each interval							
	Gran Canaria	Lanzarote	Fuerteventura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
< 25	2			1	1			4
>25 < 50	12	2	1	23	9	5	2	54
>50	8	5	5	7	4	1	1	31
Average roof area per capita, [m^2/pop]	35	61	66	40	37	40	55	41

The criteria utilized to classify the different municipality types are listed below.

Tourist: municipalities where the tourist area is bigger than 50% of the residential area.

Rural: disperse architectural distribution and predominance of one-family houses instead of apartment buildings. Values of population density lower than 200 persons/km^2.

City: higher compactness (higher percentage of high-rise apartment buildings) and higher population density than in urban areas. In particular the criteria are: population density higher than 1,000 persons/km^2 and population density per roof area higher than 40,000 persons/km^2 (which is the same as establishing a roof area per capita lower than 25 m^2).

Urban: the urban municipalities are the ones that cannot be classified within the three categories mentioned above. In this case, the population density is higher than 200 persons/km^2 and lower than 1000 persons/km^2 and, at the same time, the roof area per capita is higher than 25 m^2.

Table 10 shows the number of each municipality type within each island. It can be observed that capital islands have a higher percentage of cities and urban municipalities. Rural islands have the highest percentage of rural municipalities. Finally, tourist islands have the highest percentage of tourist municipalities.

Table 10. Municipality types

Municipality type	Gran Canaria	Lanzarote	Fuerteventura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
Urban	14	5	3	25	5	1		53
Rural	3	1	1	3	7	5	3	23
Tourist	2	1	2	2	1			8
City	2			1	1			4

A sample of municipalities, within each municipality type, has been selected to find representative values of building types for each municipality type. After processing the data, Table 11, [22] shows the distribution of building types within each municipality type.

Table 11. Distribution of building types within each municipality type, [22]

Municipality type	Apartment buildings	Terraced houses	Detached houses
Urban	45%	40%	15%
Tourist	40%	45%	15%
Rural	20%	30%	50%

Available roof area for PV. The calculation of the available roof area for PV purposes per municipality is a function of the utilization factors and the municipality type. The available roof area per island and per surface type within each island is summarized in Table 12, [22].

Table 12. Available roof surface for PV per island, [22]

Surface type	PV available roof surface, [km^2]							
	Gran Canaria	Lanzarote	Fuerteventura	Tenerife	La Palma	La Gomera	El Hierro	Total
Industrial	5.7	1.2	1	8.1	0.6	0.15	0.07	16.8
Services	2.9	0.8	0.6	4.4	0.2	0.7	0.05	9.1
Tourist	0.7	0.3	0.3	0.5	0.03	0.18	0.01	1.8
Residential	5.4	1.7	1.2	6.3	0.7	0.2	0.14	15.6
Total	14.7	3.9	3.1	19.2	1.5	0.5	0.26	43.4

The total roof that is available for PV is about 43 km^2, half of the total roof surface, which is 86 km^2. Therefore, a quick ratio to estimate the available roof surface for PV is to consider the PV available roof surface as 50% of the total roof surface. Although this percentage varies from island to island (from 43% to 53%) the 50% seems to be an adequate and easy rule of thumb.

Table 12 shows that the available industrial area (16.8 km^2) is higher than the residential one (15.6 km^2), contributing to a relevant part of the potential PV production.

Combining available PV roof surface and population data, one can calculate the PV available roof surface per capita, which is, on average, 20 m^2 per person. This ratio means that, on average, nearly 3 kW_p PV roof could be installed per person (considering that one kW_p PV occupies about 7 m^2). Table 13 shows this ratio per island and the regional average. It can be observed that tourist islands exhibit a higher ratio of available PV roof per capita. The logic behind is that in the tourist islands there are more touristic buildings, therefore more available roof area, which, divided per person (total population accounts only for local populations, not for tourists) results in a higher roof-population ratio.

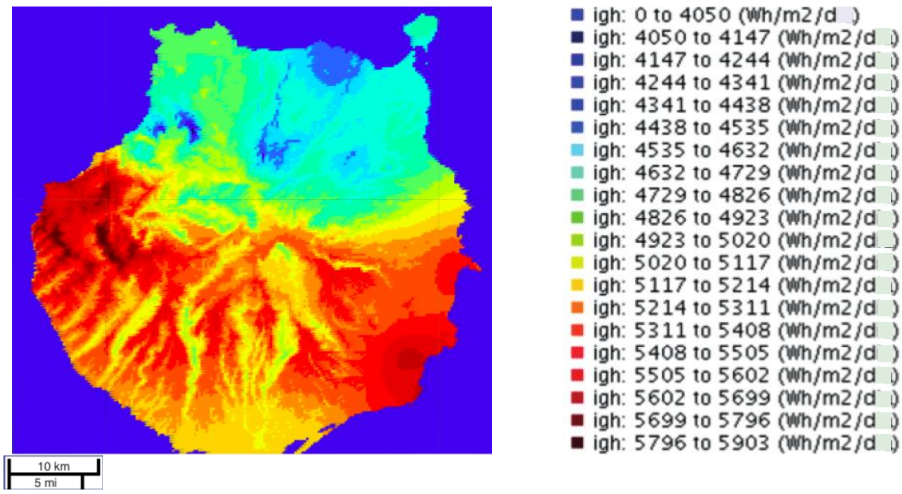
Table 13. Available PV roof-population ratio per island

	Gran Canaria	Lanzarote	Fuerteventura	Tenerife	La Palma	La Gomera	El Hierro	Canary Islands
PV available roof surface per capita, [m^2/person]	17	28	31	21	18	20	23	20

Mean global solar irradiation. The mean global solar irradiation on the horizontal plane per municipality can be obtained from the radiation map of the Canary Islands developed by the Instituto Tecnológico de Canarias (ITC) –map available at: http://meteodata.itccanarias.org/–.

The optimal slope applying Equation 1 is 23º (taking into account that the mean latitude in the Canary Islands is 28).

For each municipality, the mean global solar irradiation on the optimal tilted plane has been calculated as a function of the solar irradiation on the horizontal plane using Equation 2. Table 14 shows the mean daily global solar irradiation on a 23º tilted plane, annual average, $G_{d,a}$ (23º), for the settlements with the highest and the lowest solar irradiation in each of the Canary islands.



Source: http://meteodata.itccanarias.org/

Figure 1. Mean daily global irradiation (annual average) on the horizontal plane, Gran Canaria (Wh/m^2·*d*)

Table 14. Solar irradiation in a sample of settlements

Municipality	Island	$G_{d,a}$ (23º), [Wh/m^2·d]
La Aldea de San Nicolás	Gran Canaria	6534
Pájara	Fuerteventura	6153
San Sebastián	La Gomera	5980
Vilaflor	Tenerife	5932
El Pinar	El Hierro	5882
Antigua	Fuerteventura	5814
Haría	Lanzarote	5657
Llanos de Aridane	La Palma	5647
/…/[*]		
Arrecife	Lanzarote	5587
La Orotava	Tenerife	4886
Arucas	Gran Canaria	4845
Valverde	El Hierro	4774
Barlovento	La Palma	4685
Hermigua	La Gomera	4684

Table 15 shows the mean daily global solar radiation on a 23º tilted plane, annual average, $G_{d,a}$ (23º), calculated as the average of the radiation in the main settlement within each municipality for each island. As it can be observed, the western islands (the rural islands and Tenerife) have, on average, less solar radiation than the eastern islands.

Table 15. Average solar irradiation per island

Island	Tenerife	La Palma	La Gomera	El Hierro	Gran Canaria	Fuerteventura	Lanzarote	Canary Islands
$G_{d,a}$ (23º), Wh/m^2·d	5350	5156	5218	5339	5381	5906	5638	5377

[*] Midrange municipalities are not shown

Yearly PV production. The yearly PV production per municipality is calculated from the data obtained from the previous two steps, considering the two different scenarios defined previously.

Table 16 shows the available roof area for PV production in the selected case scenarios. The results show that, from a total roof surface of 87.6 km^2, the available roof surface for PV facilities (according to scenario 1) is 43.4 km^2, a little less than half of the roof surface. As per scenario 2, the available roof surface is 39.1 km^2, representing nearly 45% of the total roof area.

The total annual energy PV production has been calculated using Equation 3. Table 17 shows the annual potential PV production for a sample of municipalities, showing some municipalities with the highest and with the lowest potential PV production.

Table 16. Available roof surface per scenario, [22]

Scenario	Available roof surface, [km^2]							
	Gran Canaria	Lanzarote	Fuerte-ventura	Tenerife	La Palma	La Gomera	El Hierro	Total
Scenario 1	14.8	3.9	3.2	19.3	1.5	0.45	0.26	43.4
Scenario 2	13.1	3.7	3.0	17.5	1.4	0.41	0.24	39.1

Table 17. Annual PV production in some municipalities

Municipality	Island	Available roof surface, [km^2]	Global Irradiation, 23º ($Wh/m^2 \cdot d$)	Annual PV production, (GWh/a)	
				Scenario 1	Scenario 2
Las Palmas de Gran Canaria	Gran Canaria	4.94	5057	1287	1087
S/C de La Laguna	Tenerife	2.96	5424	827	742
S/C de Tenerife	Tenerife	2.79	5317	764	642
Telde	Gran Canaria	2.3	5371	638	582
Arona	Tenerife	1.94	5854	584	536
S. B. de Tirajana	Gran Canaria	1.65	5534	471	441
Adeje	Tenerife	1.46	5647	425	400
/…/[†]					
Puntagorda	La Palma	0.026	5340	7.4	6.1
Artenara	Gran Canaria	0.025	5376	7	5.6
Tejeda	Gran Canaria	0.020	5234	5	4.3
Agulo	La Gomera	0.017	4734	4.3	3.7

It should be highlighted that the municipalities with the highest potential PV production are not the ones with the highest solar radiation but with the highest available roof area.

Table 18 shows the potential PV production in the two considered scenarios, in comparison to the electricity demand per island (year 2012) and the percentage of electricity that PV could theoretically satisfy. The comparison is done at the island level since the islands are not interconnected, except for Lanzarote and Fuerteventura, which are connected by a submarine cable and are, therefore, considered one electrical system.

[†] Midrange municipalities are not shown

Table 18. Annual islands' PV production in the two case scenarios

Island	PV production, (GWh/a) or %		Electricity demand 2012, [GWh]
	Scenario 1	Scenario 2	
Gran Canaria	4055 / 116%	3702 / 106%	3493
Lanzarote - Fuerteventura	2103 / 143%	2016 / 137%	1467
Tenerife	5466/ 154%	4957 / 140%	3546
La Palma	416 / 160%	369 / 142%	260
La Gomera	121 / 168%	109 / 152%	72
El Hierro	69 / 157%	63 / 144%	44
TOTAL	12,229 / 138%	11,216 / 126%	8883

As Table 18 shows, the PV potential is very high; theoretically it could satisfy all the electricity demand in each island, even if the roof surface were shared with other uses. The total installed PV power on roofs could reach 6200 MW at regional level.

PV COST-RESOURCE CURVES AND MARGINAL COST IN THE CANARY ISLANDS

Cost-resource curves describe the amount of energy that can be obtained at a certain cost level [26]. The cost-resource curves calculated in this study are static cost-resource curves assuming current techno-economic parameters (2012).

The PV electricity generation cost is calculated for each municipality based on the economic parameters shown in Table 19 (for a justification of the selected parameters see [22]).

Table 19. Solar PV techno-economic parameters

Technology	Investment (I_0)	*O&M* costs	Life-time
	(€/kW$_p$)	*(€/(kW$_p$*a))*	*(a)*
Roof-integrated PV plant Monocrystalline silicon	1800	1% I_0	25

The production cost of PV electricity (€/kWh) is calculated as:

$$C_i = \frac{(a \times I \pm C_{OM})}{h_{eq}} \tag{4}$$

where Ci is production cost of PV electricity [€/kWh], a is annuity factor, I is investment cost [€/kWp], *r* is interest rate, in this case 6%, LT is lifetime (*a*), $C_{O\&M}$ is operation and maintenance cost (€/kW$_p$·a), h_{eq} is annual equivalent hours (h/a).

Annual equivalent hours are calculated as follows:

$$h_{eq} = \frac{(I_{md} \times 365 \times e \times PR \times r_{s-p})}{1000} \tag{5}$$

where *Imd* is mean daily global radiation on optimally tilted plane, annual average (Wh/m^2·d), *e* is module efficiency. In this case, monocrystalline silicon modules: *e* = 21.4%, *PR* is performance ratio of 0.66 (as stated in the previous section), r_{s-p} is relation surface/power. In this case, $r_{s\text{-}p} = 7$ m^2/kWp. For a discussion of the selected parameters see [22].

The results of the static cost-resource curves are represented as a stepped function (see Figures 2 and 3). In case of solar PV, sites with the same range of solar radiation are represented by one band and, hence, a stepped curve emerges [26].

Figure 2 shows the electricity generation costs of the PV systems that could be installed on the buildings' roofs in the Canary Islands. Figure 3 shows the electricity generation costs but referred to the installed power instead of electricity production.

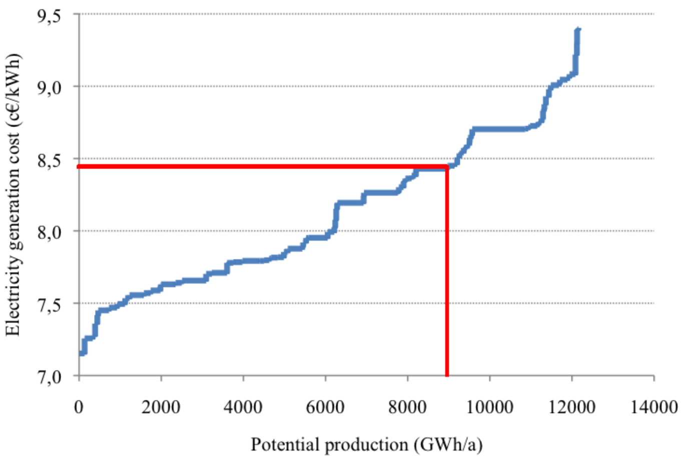


Figure 2. PV electricity production cost

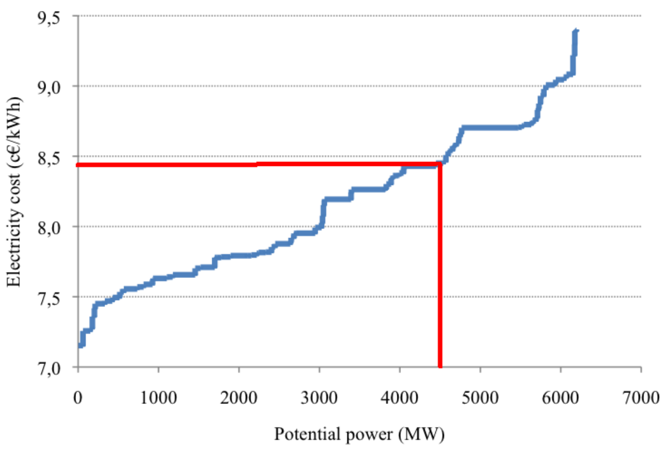


Figure 3. PV power cost

The electricity demand in the Canary Islands in 2012 was 8,883 GWh. This means that the PV marginal cost to meet this demand, according to Figure 2, is around 8.4 c€/kWh, corresponding to an installed PV power of 4500 MW (see Figure 3). The average electricity cost in 2011 in the Canary Islands was 20 c€/kWh [2]. In comparison to the current electricity prices, PV roofs seem competitive. In any case, the interpretation of these data cannot be done literally. They represent the cost of PV roofs, but massive integration of PV systems in isolated/weak grids will lead to higher costs. First at all, each island should be analysed individually, and the marginal cost for each island is different, since they are not interconnected (except for Lanzarote and Fuerteventura). Table 20 shows the marginal cost for each island. In Fuerteventura, where the cost for installing PV is the lowest of all islands, the PV cost varies from 7.15 to 7.5 c€/kWh. Both tourist islands, Fuerteventura and Lanzarote, show the lowest marginal cost, 7.5 c€/kWh and 7.8 c€/kWh, respectively. The rural islands, La Gomera, La Palma and El Hierro, show the highest marginal cost, from 8.8 c€/kWh to 9.2 c€/kWh.

Table 20. Marginal PV cost

	Gran Canaria	Lanzarote	Fuerteventura	Tenerife	La Palma	La Gomera	El Hierro	Total
Electricity demand, [GWh] in 2012	3,493	833	634	3,546	260	72	44	8,883
PV marginal cost, [c€/kWh]	8.7	7.8	7.5	8.3	8.8	8.8	9.2	8.38

On the other hand, since the islands' electrical systems are isolated ones, storage systems, combination with other energy sources and grid reinforcements should also be considered. All these measures would enable a larger exploitation of the PV potential but also increasing the systems' costs. The storage system will depend, to a great extent, on how the PV production matches the demand. This issue is analysed in the next section.

DOES PV PRODUCTION MATCH ELECTRICITY DEMAND?

Monthly approach

Previous sections showed that PV could produce even more electricity than demanded in all islands. But this does not mean that PV alone could meet the electricity demand since solar photovoltaic is an intermittent source of energy which is not available by demand 24 hours a day, 365 days a year. Therefore, PV energy has to be combined with other sources of energy and storage systems in order to maximize its contribution.

A first approach to establish the correlation between PV production and electricity demand has been done on a monthly basis. For this purpose the monthly PV production in each island has been compared to the monthly electricity demand.

The island with the highest PV potential production in comparison to its demand is analysed, which is the island of Fuerteventura. The island of Fuerteventura has a potential PV production higher than 150% of its electricity demand in the year 2012. Figure 4 shows the monthly PV production on a 23º-inclined surface in this island in comparison to its electricity demand. It shows also that, even if the annual PV production is 150% times higher than the electricity demand, there are some months when the PV production is smaller than the electricity demand. These months are November, December and January.

This behaviour can also be observed in the other islands where PV production is not as high, in percentage terms, as in Fuerteventura. Therefore, it can be concluded that, even if the annual PV production is higher than the annual electricity demand, there are some months during the wintertime when the PV production does not cover the whole demand. Therefore, some seasonal storage may be considered or the combination with other energy sources that may complement PV during the winter months and avoid overproduction during the summer time.

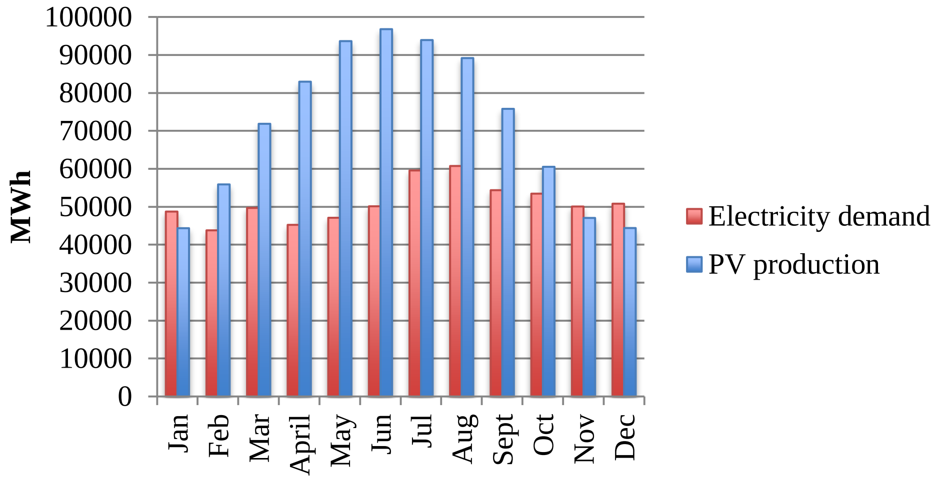


Figure 4. Monthly PV production in Fuerteventura compared to its electricity demand

Daily approach

Aside from the uneven distribution of the monthly PV production and its seasonal behaviour, the daily PV production (which is directly proportional to the solar radiation) has also a characteristic profile: zero electricity production during the hours when there is no solar radiation (e.g. during the night-time), a progressive increase of the PV production till mid-day (solar time) followed by a decrease of the electricity production afterwards.

Figure 5 (upper graph) shows the typical daily profile on a complete clear day, corresponding to the 28th of June 2010 in Pozo Izquierdo (Gran Canaria). In order to get this well-defined solar radiation curve (no small peaks along the curve) the sky has to be very clear, without a cloud in the sky. Figure 5 (lower graph) shows also the electricity demand in Gran Canaria the same day. Comparing both graphics, it is clear that the electricity demand and the PV production do not match. Both graphics show the time (horizontal axis) in local time (GMT + 1, for the summer time). Fortunately the mid-day peak coincides for both, demand and production, but for the rest of the day the disparity is obvious (no production during the night-time or during the second peak, around 21.30 hours). Therefore, daily storage, capable of storing electricity for many hours (e.g. from day-time to night-time) and/or combination with other sources of energy is needed.

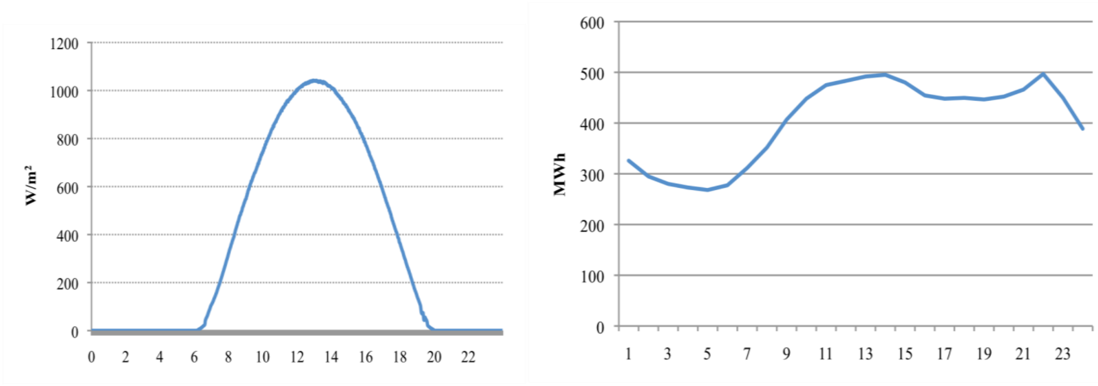


Figure 5. Solar irradiation (left) and electricity demand (right) on the 28th of June 2010 (clear sky)

Another interesting case to be analysed is that of a cloudy day with some bright spells during autumn. There are some differences, like less solar hours, which means lower match between PV production and electricity demand. Figure 6 shows the solar radiation and the electricity demand the 24th of October 2010 in Pozo Izquierdo (Gran Canaria). In this particular day, what is even more important than the number of solar hours is the type of day: cloudy with some bright spells. On days like this, not just demand and production miss-match, more importantly, there are a lot of very rapid fluctuations (in terms of seconds) in the PV production because of the changes in the amount of solar radiation that reaches the earth surface when the sky is clear at one moment and the next moment a cloud is passing by. In this case also a storage system could be useful, particularly in a building integrated system. The storage system needed may not be a daily one, but one that should be capable of absorbing the instant fluctuations of the production, providing a stable generation according to the demand (in this case, the system may not be able to store enough electricity to satisfy the night-time demand, but it may be dimensioned to absorb fluctuations during the day-time). The combination with other energy sources is also an option.

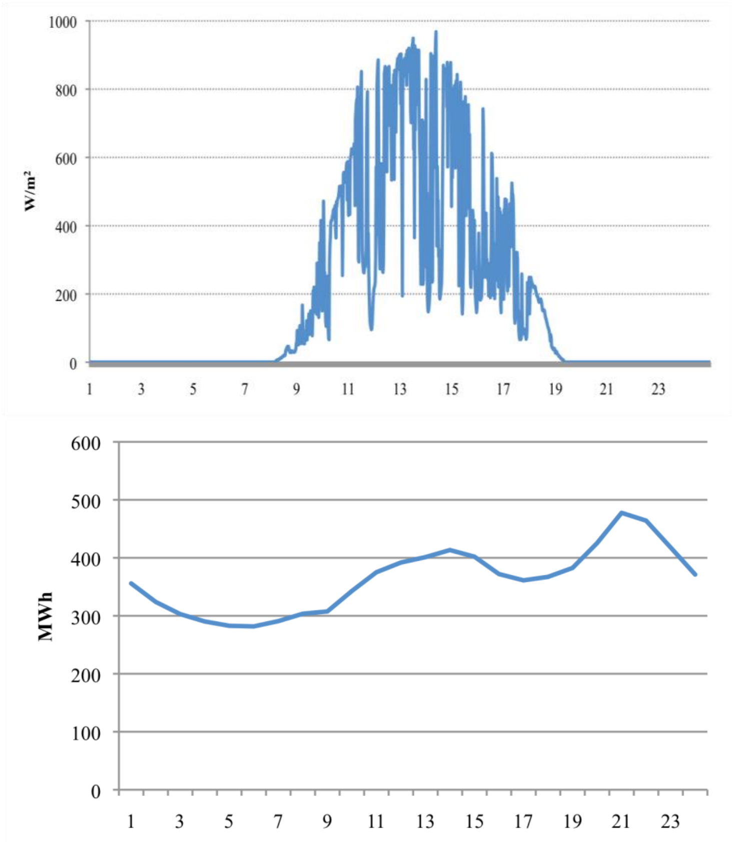


Figure 6. Solar irradiation & electricity demand, 24th October 2010 (cloudy & bright spells)

CONCLUSIONS

The Canary Islands have high solar radiation, no conventional energy sources, high population density and high percentage of natural protected areas, which ultimately lead to land scarcity. These are, among others, some of the reasons to foster PV roofs. The scale of the targeted area and the available data determine which method should be used to calculate the PV potential in roofs. The scale of this study is the island and small/medium region scale. The data available are: buildings' surfaces as per Cadastre data and the annual solar radiation on the horizontal plane from the solar map of the Canary Islands. These data have been used to calculate the potential PV production on roofs.

Although the islands belong to the same region and share a lot of common characteristics, there are also inherent differences among the islands which lead to a classification of the islands as: capital, rural and tourist islands.

On average, the industrial areas account for 21% of the total built surface, services areas account for 18% of the total area, tourist areas for 6.5% and private-residential areas for 54%.

The total roof surface is 88 km^2. The average roof surface per capita is 41 m^2/person. There is also a difference depending on the island type: the island that exhibits the lowest ratio is Gran Canaria (one of the capital islands), with only 35 m^2 roof surface per person, and the island with the highest ratios are the touristic islands, both over 60 m^2/person. These ratios are coherent, since tourist islands have lower population density than capital islands.

The available roof surface for PV facilities is about 40 km^2, a little less than half of the roof surface. Therefore, a quick ratio to estimate the available roof surface for PV is to consider the PV available roof surface as 50% of the total roof surface. Although this percentage varies from island to island (from 43% to 53%) the 50% figure seems to be an adequate and easy rule of t

humb. Another indicator is the PV roof surface per capita which is, on average, 20 m^2/person. This ratio means that nearly 3 kW$_p$ PV roof could be installed per person. Although this ratio also varies depending on the island type, the tourist islands exhibit a higher ratio of available PV roof per capita (28 to 31 m^2 per person), which is logical, since in the tourist islands there are more touristic buildings and, therefore, more available roof area, which, divided per person results in a higher roof-population ratio.

On a regional average the available roof surface is enough to meet the electricity demand (2012) of the Canary Islands, nearly 9000 GWh, even if part of the available roof surface is used for solar thermal systems and some roof space is kept free for other purposes. For each island, PV roofs could theoretically satisfy all the electricity demand, even if the roof surface were shared with other uses. The potential PV power on roofs is 6,200 MW at regional level.

Anyhow, even if the PV potential is enough to cover the annual electricity demand, the PV generation is irregular, on a seasonal and on a daily basis. Depending on the season, there will be some months during winter when the PV production will not meet the electricity demand while, during other months, there will be a PV overproduction. A similar pattern occurs on a daily basis. Even if the PV production during one day is enough to cover the daily demand, there will be some hours when the PV production will not meet the demand and other hours, during the same day, when there will be a PV overproduction. Therefore, PV production has to be combined with storage systems and/or other sources of energy, renewable or not, in order to maximize its contribution.

The economic assessment shows the cost of PV roofs in the Islands. To meet the electricity demand in the Canary Islands, 9,000 GWh in 2012, the marginal cost of PV on roofs is around 8.4 c€/kWh, which is competitive in comparison to the current electricity cost of 20 c€/kWh in the Canary Islands. This is the PV marginal cost as a regional average but this figure changes from island to island. In Fuerteventura, where the cost for installing PV is the lowest of all islands, the PV cost varies from 7.15 to 7.5 c€/kWh. Both tourist islands, Fuerteventura and Lanzarote, show the lowest marginal cost, 7.5 c€/kWh and 7.8 c€/kWh, respectively. The rural islands, La Gomera, La Palma and El

Hierro, show the highest marginal cost, from 8.8 c€/kWh to 9.2 c€/kWh. It must be pointed out that this cost represents the production cost of PV facilities but not the cost of massive integration of PV into weak electrical grids, which would be higher.

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