CALCULATION OF PV POTENTIAL MAPS IN THE CANARY ISLANDS

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ABSTRACT: This paper presents the method used for calculating the PV potential maps in the Canary Islands, Spain. The main input factors used for determining the PV potential are solar radiation data and ambient temperature data obtained from ground stations, as well as the atmospheric linke turbidity factor and the digital elevation map of the Canary Islands. The procedure followed is based in the method used previously by some authors (Suri et al) for calculating the PV potential in Europe and Africa but with some modifications in the model. For the estimation of the PV potential, the ambient temperature is taken into account in the performance ratio.

Keywords: Solar Radiation, Performance, Simulation

1 INTRODUCTION

Four different PV systems are evaluated in this work: fixed at optimum inclination, azimuthal tracking, polar tracking or double axis tracking. The method used for determining the PV potential maps for the Canary Islands is based on the approach previously carried out by other authors for Europe[1] and Africa[2].

The solar radiation calculation model is the one proposed by J. Hofierka and M. Súri in the open source GIS software GRASS[4,5] within the module r.sun. The s.vol.rst and s.sruf.rst modules of GRASS are also used for interpolation using regularized splines with tension of some parameters.

The main differences of the method followed in this study compared with previous works are:

On the one side, calculations have been carried out for the mean day of each month, instead of integrating for the whole month. The mean day of the month is defined as the day for which the solar declination has the mean value of that month[3]. This way, we have saved a lot of computing time, which for a grid of 50x50m map was critical, especially for the hilly and mountainous islands.

On the other side, the temperature effect has been taking into account in the model for the final yield, as well as other parameters, which have different impacts in the performance of the four different PV systems studied.

The sub index i in the text of this paper stands for the month value (from 1 to 12).

2 PRIMARY DATA SOURCES

There are four main input variable sets in the model: solar radiation data, ambient temperature data, linke turbidity factor and digital elevation maps of the Canary Islands. It is significant the effort carried out in this project for obtaining good quality data from these four data sets.

2.1 Solar Radiation Data

There are some previous solar radiation databases which include the Canary Islands, such as SoDa and PV-GIS projects. The main problem with these databases is that they do not have enough resolution. They normally obtain the primary data from satellite sources that are quite coarse for the geographical and meteorological characteristics of the Canary Islands.

An effort has been carried out to detect 97 ground stations recording good quality horizontal global irradiance from different organizations and different time periods ranging from 1 to 10 years data.

The monthly averages of daily sums of global horizontal radiation of these stations were computed ($H_{hs,i}$). Each monthly value from each station has only been considered when at least three years of data were available.

2.2 Ambient Temperature Data

The monthly means of the maximum daily ambient temperature ($T_{MAX,i}$) and the monthly means of the minimum daily ambient temperature ($T_{min,i}$) were obtained from 280 ground stations from different organizations and different time periods, also ranging from 1 to 10 years data. Like in the previous data set, each monthly value from each station has only been considered when at least three years of data were available.

2.3 Linke Turbidity Factor

The Linke turbidity factor is a very convenient approximation to model the atmospheric absorption and scattering of the solar radiation under clear sky conditions. l'École des Mines de Paris under the SoDa project has provided this data for the whole world in a resolution of 5' x 5'. The files contain the twelve monthly values of the Linke turbidity factor ($T_{LK,i}$).

2.4 Digital Elevation Maps

The Digital Elevation Maps (DEM) from the Canary Islands were provided with a grid resolution of 50x50 m by GRAFCAN, the Canary Islands Government Cartography company.

3 METEOROLOGICAL DATA PROCESSING

3.1 Normalized Linke Turbidity Factor

The linke turbidity factor values are normalized to sea level according to:

$$T_{LKn,i} = T_{LK,i} + 0.00035z \quad [1]$$

where z is the elevation for each data point. The normalized linke turbidity factor is then two-dimension interpolated using regularized splines with tension (module v.surf.rst from GRASS software) and monthly atmospheric linke turbidity maps are obtained.

3.2 Global Horizontal Radiation

Calculation of Clear Sky Global Horizontal Radiation ($H_{hc,i}$) has been carried out using the normalized linke turbidity factor and the r.sun module of GRASS integrating the beam ($B_{hc,i}$) and diffuse ($D_{hc,i}$) components every 15 minutes:

$$H_{hc,i} = B_{hc,i} + D_{hc,i} \quad [2]$$

The clearness index is calculated dividing the Global Horizontal Radiation obtained from the ground stations ($H_{hs,i}$) and the Clear Sky Global Horizontal Radiation ($H_{hc,i}$):

$$k_{c,i} = H_{hs,i} / H_{hc,i} \quad [3]$$

Finally, the Clearness Index is interpolated using three dimensional regularized splines (v.vol.rst module from GRASS) and the final Global Horizontal Radiation Map is calculated according to:

$$H_{h,i} = k_{c,i} \cdot H_{hc,i} \quad [4]$$

3.3 Global Radiation at PV module collecting plane

Using the Page correlation, the Diffuse Horizontal Radiation ($D_{h,i}$) is estimated as:

$$D_{h,i} = H_{h,i} [1 - 1,13 (H_{h,i} / B_{Oh,i})] \quad [5]$$

Where $B_{Oh,i}$ is the Horizontal Extraterrestrial Radiation (see table I). The Diffuse Clearness Index ($k_{c,i}^d$) is calculated according to:

$$k_{c,i}^d = D_{h,i} / D_{hc,i} \quad [6]$$

And the Beam Clearness Index ($k_{c,i}^b$):

$$B_{h,i} = H_{h,i} - D_{h,i} \quad [7]$$

$$k_{ci}^b = B_{h,i} / B_{hc,i} \quad [8]$$

Introducing the Diffuse Clearness Index and the Beam Clearness Index in the r.sun module of GRASS, the beam, diffuse and ground reflected irradiances are computed. The azimuth and elevation values of the collecting plane are introduced in the clear sky model, according to the type of PV system (fixed at optimum inclination, azimuthal tracking, polar tracking or double axis tracking). The albedo value used for the calculations is 0.20. The beam, diffuse and ground reflected radiations (B_i, D_i and R_i) are obtained integrating the corresponding irradiances every 15 minutes for the mean month day.

Finally, the Global Radiation over the collecting plane is calculated as:

$$G_i = B_i + D_i + R_i \quad [9]$$

3.4 Diurnal Ambient temperature

The maximum ambient temperature data is calculated by interpolating three dimensional regularized splines with tension of the monthly means of the maximum daily ambient temperature ($T_{MAX,i}$). The same is carried out with the monthly means of the minimum daily ambient temperature ($T_{min,i}$). In both cases, a 0.01 value has been chosen for the smooth interpolation factor if there are 5 or more months of data available, 0.10 if there are 4 months and 0.20 if there are 3 months.

Monthly Means of the Diurnal Ambient Temperature ($T_{md,i}$) are then calculated according to:

$$T_{md,i} = C_i (T_{MAX,i} - T_{min,i}) + T_{min,i} \quad [10]$$

Where Ci is a constant depending on the month chosen (see table I). This constant has been calculated supposing that the temperature behavior evolves like two semi-cycles of two cosine functions, according to the model proposed by E. Lorenzo[3], where the minimum ambient temperature happens at sun rise and the maximum two hours after solar noon.

4 PV POTENTIAL ESTIMATION

The Final Yield for each month (Y_{Fi}) and annually (Y_F) is calculated according to:

$$Y_F = \sum_i^{12} Y_{Fi} \quad [11]$$

$$Y_{Fi} = n_i G_i PR_i / 1000 \quad [12]$$

Where n_i is the number of days of month i. This process is carried out for the Global Radiation of each PV system (fixed at optimum inclination, azimuthal tracking, polar tracking or double axis tracking) (G_i).

PR_i is the performance ratio of month i composed by:

$$PR_i = P_{TEMP,i} P_{FRE,i} P_{CC,i} P_{DIS,i} P_{INV,i} \quad [13]$$

4.1 Temperature losses

$P_{TEMP,i}$ is the performance due to the temperature losses in the modules and has been calculated according to:

$$P_{TEMP,i} = 1 - (T_{pm,i} - 25) C_{temp} \quad [14]$$

C_{temp} is the module power temperature coefficient that is set to a typical value of $0{,}0043ºC^{-1}$. $T_{pm,i}$ is the mean temperature of the module that has been calculated for the mean day of each month like:

$$T_{pm,i} = G_i / h_i (NOTC - 20) / 800 + T_{md,i} \quad [15]$$

Where NOTC is the Normal Operation Temperature which has been set to a typical crystalline silicon module value of 46ºC and h_i is the mean day duration of month i (see table I).

4.2 Fresnel losses

$P_{FRE,i}$ is the performance due to the fresnel losses in the module. The model used for the transmittance is the one used in the ASHRAE[6] for thermal collectors with a b_0 parameter of 0.05. The fresnel losses have been evaluated for the mean day of each month and for each of the PV systems (fixed at optimum inclination, azimuthal tracking, polar tracking or double axis tracking).

4.3 Serial Resistance losses

$P_{CC,i}$ is the performance due to interconnections serial resistance losses and has been considered constant and equal to 0.975 (2.5% losses).

4.4 Dispersion losses

$P_{DIS,i}$ is the performance due to the dispersion losses of the modules and has been considered constant and equal to 0.98 (2.0% losses).

4.5 Inverter losses

$P_{INV,i}$ is the performance due to the inverter losses. A typical inverter efficiency curve has been used for this purpose and evaluated for the four different PV systems (fixed at optimum inclination, azimuthal tracking, polar tracking or double axis tracking). The efficiency model used is the one proposed by E.Lorenzo[3] with k_0, k_1 and k_3 factors of 0.020, 0.025 and 0.025 respectively. The efficiency has been evaluated considering that the nominal power of the inverter is the one obtained for the maximum power of the system at noon of the maximum monthly mean day of the year.

5 RESULTS

Table I, II and III shows the parameters used during the calculation process for the mean day of each month and the Canary Islands mean latitude (28.45ºN).

Table I: Mean month day, temperature parameter for diurnal temperature calculations (C_i), horizontal extraterrestrial radiation ($B_{Oh}(0)$) and daylight duration (h_i), all of then calculated for the Canary Islands mean latitude 28.45ºN and mean day of the month.

Month	Mean Month Day	Day of the year	C_i	$B_{Oh}(0)$ (Wh/m^2)	h_i (hours)
January	17	17	0.648	6184	10.42
February	15	46	0.644	7480	11.07
March	16	75	0.652	9034	11.87
April	15	105	0.650	10350	12.71
May	15	135	0.653	11119	13.42
June	11	162	0.649	11379	13.78
July	17	198	0.646	11201	13.62
August	16	228	0.646	10586	13.02
September	16	259	0.649	9448	12.20
October	16	289	0.651	7958	11.36
November	15	319	0.643	6514	10.61
December	11	345	0.643	5791	10.23

Table II: Performance due to the fresnel losses, $P_{FRE,i}$, for the Canary Islands mean latitude 28.45ºN and mean day of the month.

Month	Fixed System	Azimuthal Tracking	Polar Tracking	Double Axis Tracking
January	0.948	0.988	0.992	1.000
February	0.926	0.989	0.994	1.000
March	0.913	0.991	1.000	1.000
April	0.898	0.993	0.993	1.000
May	0.914	0.994	0.982	1.000
June	0.886	0.994	0.989	1.000
July	0.883	0.993	0.991	1.000
August	0.902	0.993	0.989	1.000
September	0.887	0.991	0.999	1.000
October	0.934	0.990	0.997	1.000
November	0.937	0.987	0.992	1.000
December	0.944	0.986	0.990	1.000

Table II: Performance due to the inverter losses, $P_{INV,i}$, for the Canary Islands mean latitude 28.45ºN and mean day of the month.

Month	Fixed System	Azimuthal Tracking	Polar Tracking	Double Axis Tracking
January	0.894	0.916	0.919	0.925
February	0.859	0.882	0.885	0.888
March	0.873	0.916	0.925	0.925
April	0.877	0.926	0.891	0.913
May	0.898	0.931	0.889	0.927
June	0.875	0.931	0.910	0.919
July	0.869	0.930	0.912	0.899
August	0.888	0.929	0.890	0.894
September	0.854	0.899	0.893	0.910
October	0.880	0.914	0.920	0.924
November	0.864	0.882	0.885	0.889
December	0.875	0.896	0.898	0.908

The final results are shown in figures 1, 2, 3 and 4 for the four different systems studied.

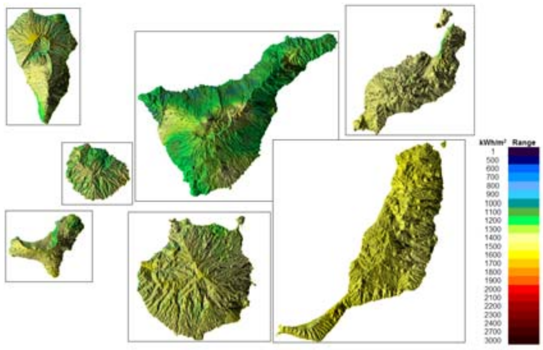

Figure 1: Final annual yield for the fixed at optimum inclination PV system.

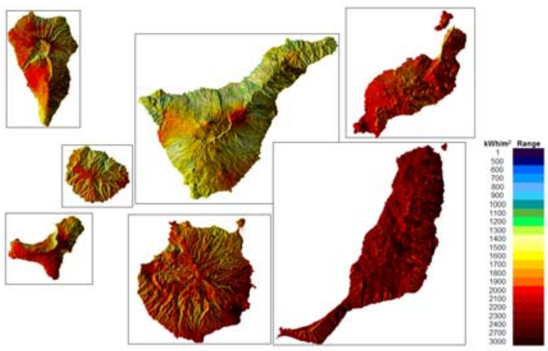

Figure 2: Final annual yield for the azimuthal tracking PV system.

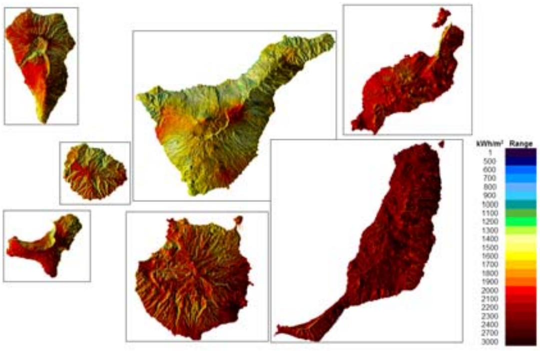

Figure 3 Final annual yield for the polar tracking PV system.

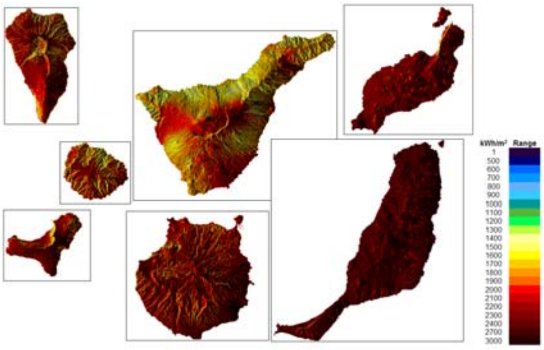

Figure 4 Final annual yield for the dual axis tracking PV system.

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