PHOTOVOLTAIC POWER ESTIMATION TOOL USING A SOLAR RADIATION NUMERICAL MODEL

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ABSTRACT: A tool based on a solar radiation numerical model for the evaluation of the suitability of different possible locations for photovoltaic power stations is presented. It allows the user to estimate the solar radiation in a given place as well as the photovoltaic power generation, and compare the results with those obtained for other locations. The solar radiation model is implemented taking into account the terrain surface with the use of 2-D adaptive meshes of triangles, which are made using a refinement/derefinement procedure according to the variations of terrain surface, orography and albedo. To find the optimal location for obtaining the maximum power generation, the effect of shadows is considered. The solar radiation is first computed for clear-sky conditions, considering the different components of radiation. The real-sky radiation is computed daily starting from the results of clear-sky radiation. The maps of clear-sky index are obtained from a spatial interpolation of observational data that are available for each day at several points of the zone under consideration. Finally, the solar radiation maps of a month are calculated from the daily results. Taking into account the photovoltaic cell model, the electric power generation can be deduced from the obtained radiation data.
Keywords: Solar Radiation, Modelling, Simulation

1 INTRODUCTION

There are three groups of factors that determine the interaction of solar radiation with the earth's atmosphere and surface (see e.g. [1, 2]):

1. The Earth's geometry, revolution and rotation (declination, latitude, solar hour angle)
2. Terrain (elevation, albedo, surface inclination and orientation, shadows)
3. Atmospheric attenuation by gases, particles and clouds

Considering the three factors of atmospheric attenuation in the model, it will produce real-sky radiation values. If we omit the cloud attenuation, clear-sky (cloudless) radiation values will be obtained.

Two main groups of spatial models for solar radiation can be found. On one hand there are those models based on the study of data obtained from satellite observations (see e.g., [3]), and, on the other, those based on astrophysical, atmosphere physical and geometrical considerations. Among that latter group, we highlight the works of Suri and Hofierka [1, 2] regarding a GIS-based solar radiation model.

In this work we propose some improvements to the models of Suri and Hofierka [1, 2] and Montero et al. [4]. The accurate definition of the terrain surface and the produced shadows are studied using an adaptive mesh of triangles.

To calculate the radiation values for real sky conditions, a typical meteorological year (TMY) for each available measurement stations has been developed following the method used in [5]. The obtained results allow us to estimate the amount of the expected electric power generation, for any day at any place in the island.

2 SOLAR RADIATION MODELLING

Starting from the work of Suri and Hofierka [1, 2], we have proposed both the use of adaptive meshes for surface discretization and a new method for detecting the shadows over each triangle of the surface [4]. Results have been improved by means of the use of TMY extracted from the available measurements stations data [5]. The calculations flow would be:

1. Solar radiation calculation for all the mesh, assuming clear sky conditions
2. TMY calculation for all the involved measurement stations
3. Correction of the solar radiation values using the measured values to reach the real sky conditions

Steps one and three are repeated for each time step and finally the total solar radiation value is obtained integrating all the instantaneous values.

2.1 Solar radiation equations for clear sky

The global solar irradiance comprises three different components: beam, diffuse and reflected irradiances. Taking into account [6], we will take the solar constant I_0 as 1367 (W/m^2) outside the atmosphere at the mean solar distance. Due to the earth's orbit eccentricity, a correction factor ε is applied for calculation of the extraterrestrial irradiance G_0.

$$G_0 = I_0\varepsilon \qquad \text{Eq. 1}$$

Where $\varepsilon = 1 + 0.03344\cos(j' - 0.048869)$, with j' being the day angle. The beam irradiance, normal to the solar beam, G_{b0} (W/m^2) is attenuated by the cloudless atmosphere, and calculated as follows:

$$G_{b0c} = G_0 \exp\{-0.8662 T_{LK} m\ \delta_R(m)\} \qquad \text{Eq. 2}$$

Using the Linke (T_{LK}) atmospheric turbidity factor and the relative optical air mass calculated using the formula:

$$m = \frac{p/p_0}{\sin h_0^{ref} + 0.506(h_0^{ref} + 6.08)^{-1.636}} \qquad \text{Eq. 3}$$

Where h_0^{ref} is the solar altitude in degrees corrected by the atmospheric refraction, and p/p_0 is a correction for a given elevation z. The beam irradiance on a horizontal surface $G_b(0)$ becomes,

$$G_{bc}(0)= G_{b0c}\, L_f \sin h_0 \qquad \text{Eq. 4}$$

Where h_0 is the solar altitude angle and L_f, the lighting factor that corrects the beam irradiance as the surface is sunlit or shadowed. Then the beam irradiance on an inclined surface $G_b(\beta)$ is obtained as,

$$G_{bc}(\beta)= G_{b0c}\, L_f \sin \delta_{exp} \qquad \text{Eq. 5}$$

Where β is the angle between the inclined surface and the horizontal, and δ_{exp} is the solar incidence angle measured between the sun beam direction and its projection on an inclined surface.

The estimation of the diffuse component in horizontal surfaces $G_{dc}(0)$ (W/m^2) is carried out using the equation,

$$G_{dc}(0)= G_0\, T_n(T_{LK}) F_d(h_0) \qquad \text{Eq. 6}$$

Where $G_{dc}(0)$ is a function of the diffuse transmission T_n which only depends on the Linke turbidity factor and on a function F_d depending on the solar altitude h_0 [7].

On the other hand, the procedure for obtaining the clear-sky diffuse irradiance on a inclined surface with an inclination angle γ_N, $G_d(\gamma_N)$ (W/m^2) considers both sunlit and shadowed surfaces [8]. For sunlit surfaces the equations are, for $h_0 \geq 0.1$,

$$G_{dc}(\gamma_N) = G_{dc}(0)\left(F(\gamma_N)(1-K_b) + K_b \frac{\sin \delta_{exp}}{\sin h_0}\right) \qquad \text{Eq. 7}$$

And, for $h_0 < 0.1$,

$$G_{dc}(\gamma_N) = G_{dc}(0)\left(F(\gamma_N)(1-K_b) + \frac{K_b \sin \gamma_N \cos A_{LN}}{0.1 - 0.008 h_0}\right) \qquad \text{Eq. 8}$$

For shadowed surfaces, $G_{dc}(\gamma_N) = G_{dc}(0)F(\gamma_N)$.

$$F(\gamma_N) = r_i(\gamma_N) + N\left(\sin \gamma_N - \gamma_N \cos \gamma_N - \pi \sin^2 \frac{\gamma_N}{2}\right) \qquad \text{Eq. 9}$$

$$r_i(\gamma_N) = \frac{(1+\cos \gamma_N)}{2} \qquad \text{Eq. 10}$$

The parameter $K_b = G_{bc}(0)/G_0(0)$ and the irradiation $G_0(0) = G_0 \sin h_0$. The reflected irradiation is calculated according to [9], taking into account the mean ground albedo ρ_g.

$$G_r(\gamma_N) = \rho_g G_c(0) r_g(\gamma_N) \qquad \text{Eq. 11}$$

$$r_g(\gamma_N) = \frac{(1-\cos \gamma_N)}{2} \qquad \text{Eq. 12}$$

$$G_c(0) = G_{bc}(0) + G_{dc}(0) \qquad \text{Eq. 13}$$

2.2 Solar radiation under real sky

To obtain the real sky values is necessary a correction due to the presence of clouds. The values of global radiation on a horizontal surface for real sky conditions $G(0)$ are calculated as a correction of those of clear sky $G_c(0)$ with the clear sky index k_c which has been studied for Gran Canaria Island [10],

$$G(0) = G_c(0) k_c \qquad \text{Eq. 14}$$

$$k_c = G_s(0)/G_c(0) \qquad \text{Eq. 15}$$

Sub index *s* means *station*. The value of the clear sky index at the measurement stations is given by Equation 15.

Now an interpolation of the index for the whole zone is needed. A simple formula that has also been used in other environmental problems defined on complex orography [11] is applied,

$$k_c = \varepsilon \frac{\sum_{n=1}^{N} \frac{k_{cn}}{d_n^2}}{\sum_{n=1}^{N} \frac{1}{d_n^2}} + (1-\varepsilon) \frac{\sum_{n=1}^{N} \frac{k_{cn}}{|\Delta h_n|}}{\sum_{n=1}^{N} \frac{1}{|\Delta h_n|}} \qquad \text{Eq. 16}$$

The parameter k_c corresponds to the clear sky index at each point of the mesh, k_{cn} is the clear sky index obtained at the measurement stations, N is the number of stations used in the interpolation, d_n is the horizontal distance and $|\Delta h_n|$ is the difference in height between station n and the studied point, respectively, and ε is a parameter between 0 and 1.

2.3 Typical meteorological year

To obtain reliable results, an accurate typical meteorological year (TMY) is needed. Autoregressive moving average (ARMA) models are widely applied to time series. To soften irregularities, moving averages have been used. These ones have been adjusted by the least-squared method. Due to the cyclical character of our series, a Fourier analysis has been chosen.

$$Y_t = \alpha_0 + \sum_{i=1}^{r} \left[\alpha_i \cos\left(\frac{2\pi i t}{T}\right) + \beta_i \sin\left(\frac{2\pi i t}{T}\right)\right] + \epsilon_t \qquad \text{Eq. 17}$$

With t=1…n, and ϵ_t fitting an ARMA model. Using the moving average method we can minimize the time series noise, transforming Y_t series in another one by means of the transformation,

$$MY_t = \sum_{j=-m}^{m} \omega_j Y_{t+j} \qquad \text{Eq. 18}$$

In this expression, ω_j are the weights for the adjusted series mean.

We compute the daily typical meteorological year of maximums, means, medians, variance and percentiles of 90% and 75% series of values. In order to improve the knowledge of solar intensities, it was obtained one TMY for each of those series using weight means to smooth the irregular data. Finally, the TMY series were fitted to third grade Fourier series, obtaining excellent results in all the locations around the island. For means, we have used the moving average M_{21},

$$\widehat{m}_d = \frac{1}{A} \sum_{a=1}^{A} M_{21} Z_{ad} \qquad \text{Eq. 19}$$

Where A is the number of years with available data, and d is the day of the year. For the median series,

$$M_d = M_{21} \cdot [median(Z_{ad})] \qquad \text{Eq. 20}$$

3 SIMULATIONS

We have obtained radiation results for Gran Canaria Island, part of the Canary Islands archipelago. The UTM coordinates (metres) that define the corners of the considered rectangular domain including the island are (417025, 3061825) and (466475, 3117475), respectively.

Using the refinemet/derefinement parameters as in [4], a mesh with 5866 nodes and 11683 triangles was built to describe the orography and albedo of the island. To define the albedo, the different types of land use in Gran Canaria Island have been studied varying from 0.05 (Macaronesic laurisilva) to 0.6 (Salt mine).

The Linke factor was obtained online from the SoDa Service [12] for each month. Beam, diffuse and reflected radiations are computed using the equations presented above, and taking into account the calculated shadow distribution on the mesh.

Then, for each day, the clear sky global radiation is computed with the desired time step, as the sum of the three components. In the studied cases, we have chosen a 30 minutes step. We have used Simpson formula to integrate these data numerically in order to obtain the daily radiations.

Once this is done, real sky values are computed using actual radiation data. Seven measurement stations around the island are available with complete data from years 1998 to 2008. Radiation data have been provided by the Canary Islands Technological Institute (ITC).

Under clear sky conditions, beam, diffuse and reflected radiation values are about $82-87\%$, $13-18\%$ and $0-0.5\%$ of the mean global radiation respectively. The monthly daily average real sky global radiation, for the whole studied region (Gran Canaria Island), varies from 10.6 MJ/m^2 per day in December, to 25.6 MJ/m^2 per day in June. The percentage of decrease between the computed real sky and clear sky radiation is presented in Fig. 1. The clearest days over the whole island are those from spring, especially during the months of May and June. We can see the typical behaviour of the cloudiness produced by the Trade Winds over the island during summer.

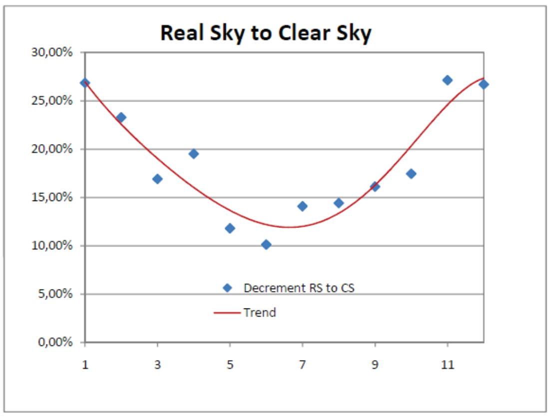

Figure 1: Percentage decrease in computed radiation

As an example, two months are presented. Fig. 2 shows the real sky radiation map for January, and Fig. 3 shows July. In this figure, the effect of the trade winds in the northeastern part of the island can be observed. In this region, a flat zone, the computed radiation is lower than expected due to the cloudiness caused by these winds.

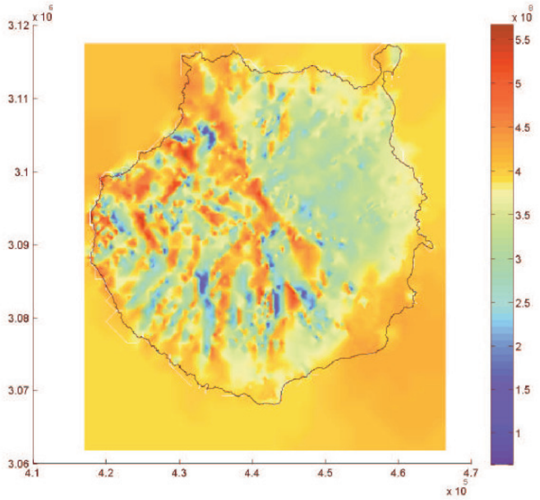

Figure 2: Real sky radiation map for January

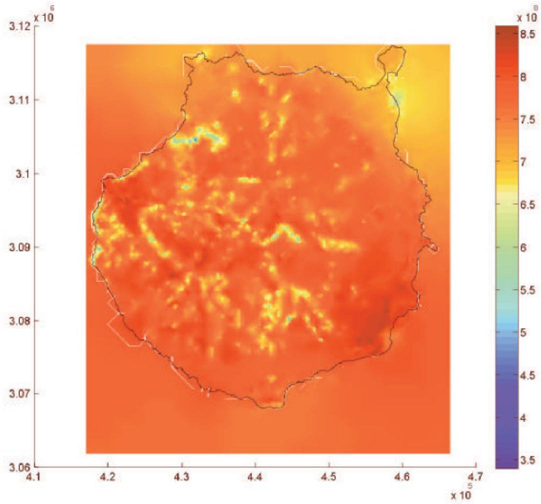

Figure 3: Real sky radiation map for July

4 CONCLUSIONS

An improved numerical model for estimating the solar radiation on a surface is proposed. The requirements for a simulation are the location, topography, albedo and observational data. Solar radiation on a surface is estimated taking into account the shadow distribution in each time step. Adaptive meshes lead to a minimum computational cost, since the number of triangles to be used is optimum.

To obtain accurate model results, realistic data are needed. A typical meteorological year (TMY) has been computed to serve as departure point to estimate the real sky radiation values. To calculate these, we propose an interpolation method which is suitable when a considerable number of stations is available and they are well distributed in the zone under study.

This model allows us to choose the most suitable zone in the island, where a photovoltaic power station can be placed according to the real sky radiation values. As seen in figures 2 and 3, real sky radiation values are available for each and every month for a TMY. This means that solar power generation can be estimated from those, taking into account the models of the different power station parts. Moreover, rectangular collectors can be included in the model as composed by two triangles in the same plane.

In the simulations we have obtained values of radiation for clear sky and real sky conditions. Real sky maps show decreased values from clear sky, with a correct behaviour. The effect of the trade winds which blow from northeast can be seen in figures 1, 2 and 3.

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