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EVALUATION OF THE SOLAR ENERGY POTENTIAL AT SURFACE IN SÃO PAULO, SP, BRAZIL

AVALIAÇÃO DO POTENCIAL DE ENERGIA SOLAR À SUPERFÍCIE NO MUNICÍPIO DE SÃO PAULO, SP, BRASIL

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SUMMARY

The aim of this study, based on data collected from a radiometric station at the Department of Atmospheric Sciences at the Geophysical and Astronomical Institute of the University of São Paulo, IAG/USP, was to develop and appraise a mathematical model for evaluation of solar energy potential in the city of São Paulo, in São Paulo State, Brazil, as a function of only one radiometric measurement at sun's meridian crossing. The values of solar energy potential calculated by the proposed methodology permit the evaluation of the maximum possible performance of energy capture systems, which is very important in engineering projects designed to make use of solar energy in all its various forms. The performance of the estimation model of maximum energy input was checked by analysis of determination coefficients (r^2) and Willmott's agreement indices (d) applied to estimated and observed data on the chosen days at the site studied. A new way of estimating the a and b parameters of the Ångström equation is proposed, which is irrespective of daily integrations and a large number of radiometric measurements, considering that such a process is a funtion of only one measurement taken at the sun's meridian crossing. The results presented show that the proposed methodology was efficient in quickly and easily evaluating of these parameters, as well as eliminating the multiple error sources produced by the conventional

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methodology. For the climatic conditions of São Paulo, capital, we can conclude that it is possible to estimate accurately the maximum daily solar energy input and that the estimation criterion of the global solar radiation based on the proposed theory generated values extremely close to those measured by accurate instruments based on thermoelectrical and photoelectrical effects.

Key words: global solar radiation, modelling, solar radiometry, flux maximum density.

RESUMO

O objetivo do trabalho foi desenvolver e aferir um modelo matemático para avaliação do potencial de energia solar diária disponível em São Paulo, em função de apenas uma medida radiométrica na passagem meridiana do sol. Utilizaram-se os dados radiométricos registrados nas estações do Departamento de Ciências Atmosféricas do Instituto Astronômico e Geofísico da Universidade de São Paulo - IAG/USP. Os valores de potencial de energia solar calculados pela metodologia proposta permitem a avaliação da máxima performance possível de sistemas de captura de energia, a qual é muito importante em projetos de engenharia voltados ao aproveitamento da energia solar em suas mais variadas formas. A performance do modelo de estimativa foi verificada através da análise dos coeficientes de determinação (r^2) e dos índices de concordância de Willmott (d) aplicada aos dados estimados e observados. Propôs-se também um novo modo de estimativa dos parâmetros a e b da equação de Ångström que independe de integrações diárias e de séries longas de medidas radiométricas, visto que tal processo é função apenas de uma medida realizada na passagem meridiana do sol. Os resultados revelaram que a metodologia, além de eliminar as múltiplas fontes de erro cometidas pela metodologia convencional é eficiente para avaliação dos referidos parâmetros com rapidez e simplicidade. Para as condições climáticas da localidade analisada, foi possível estimar-se com boa precisão o máximo "input" de energia solar diário e concluir que o critério de estimativa da radiação solar global fundamentado na teoria proposta gerou valores extremamente próximos daqueles medidos por instrumentos baseados em efeitos termoelétricos e fotoelétricos.

Palavras-chave: radiação solar global, modelagem, radiometria solar, densidade máxima de fluxo de radiação.

INTRODUCTION

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The direct determination of the availability of solar radiation in a given site throughout the year is done by means of equipments with a high degree of accuracy, such as Eppley pyranometer, or those with lower degree, as Robitzsch bimetalic actinograph. These would be the main processes used for direct evaluation of the availabilities of solar energy in Brazil, with the inconvenient of our solarimetric net, besides being insufficient in relation to the size of the territory and counting on precarious periodical calibration and conservation, is in need of equipments with a high degree of accuracy, which are, as a general rule, imported. Faced with this, the research has been looking for, using the reliable historical series, indirect estimation methods of the global solar radiation, mainly by means of heliographs, based on the classical theory (ÅNGSTRÖM, 1924), which correlates the insolation ratio with the fraction transmitted by the atmosphere at soil level.

The evaluation of the solar energy potential is currently done in Brazil by the nets of INMET (National Institute of Meteorology) and by institutions of research, using the Robitzsch bimetalic actinograph, with the number of accurate instruments still insufficient in relation to necessity, such as pyranometers and pyreliometers. To be reliable the data obtained from actinographs depends on periodical calibration, noting also that the process of integration of the diagrams on cloudy days is quite difficult, a fact that can result in appreciable errors of measurement. As the actual number of actinographs is also insufficient the extensive process of the evaluation of solar energy for irrigation, potential of agricultural production, agroclimatic zoning, etc. is still done by Campbell-Stokes heliograph, by means of the general model proposed by PRESCOTT (1940) and diffused by PENMAN (1948). Nevertheless, the difficulties relative to accuracy of the global solar radiation measured by actinograph can many times generate Angström's coefficients values, a and b, that being precariously estimated by the conventional methodology, determine great errors of evaluation.

Faced with this problem, an estimation process of the solar global radiation potential available throughout the year, similar to that one proposed by VILLA NOVA & SALATI (1977), has been developed in this paper, as a function of only one radiometric measurement at the sun's meridian crossing and a more reliable model, which dispenses the analysis of an extensive series of radiometric measurements dependent on daily integrations, has been proposed for São Paulo, SP, Brazil. The model was tested through accurate radiometer measurements obtained by pyranometers at the site studied, presenting excelent results.

MATERIAL AND METHODS

The climate of São Paulo city, São Paulo State, Brazil (latitude 23°39'S, longitude 46°37'WGr and altitude 800m) was classified, according to the Köppen System, as Cwa or subtropical with rains in the summer and dry winter. The number of insolation hours was measured with a heliograph from Wilh Lambrechet KH Göttingen type 1603; the average vector beam (r) was obtained from Anuário Astronômico published in 1980 by the Geophysical and Astronomical Institute of the University of São Paulo - IAG/USP; and the solar declination was defined by means of the following expression:

$$\delta = 23{,}45.\,sin\left[\frac{360}{365}(DJ - 80)\right] \qquad (1)$$

where DJ is the number of days computed since the first of January up to the considered date.

The extra-terrestrial radiation, expressed in KJ m^{-2} day^{-1}, was calculated by the following equation:

$$Qo = \frac{Jo}{r^2}\frac{1440}{\pi}\left[sin\delta.sin\varphi.H^* + \cos\delta.\cos\varphi.sinH\right] \qquad (2)$$

where Jo is the solar constant (83,736KJ m^{-2} min^{-1}); r is the earth-sun distance, expressed in terms of average distance; H^*, H are the semi-arcs from the meridian crossing to the sunset in radians or degrees, respectively; δ is the solar declination, in degrees; φ is the local latitude, in degrees.

The daylight length (N), in hours and tenths was expressed by:

$$N = \frac{2H}{15} = 0{,}133.H \qquad (3)$$

where:

$$H = arc\ \cos\left[-tg\delta.tg\varphi\right] \qquad (4)$$

The global solar radiation (Qg) was measured by an Eppley pyranometer, model PSP, serial number 29767 F3, resistence 728 ohm at 23°C, with a sensitivety of 8,13mV/kW m^{-2}, corresponding to a response of 5,67cal cm^{-2} min^{-1}/mV. An automatic system of data acquisition Data Logger was connected to this. The maximum intensity of global solar radiation (I_{12}) on cloudless days, at the sun's meridian crossing, was determined by a quotation of pyranometer diagrams for the selected days.

The methodology to be presented for calculating the potential of solar energy at a given site, for each period of the year consists of the following:

Denominating Jo/r^2 the instantaneous value of the direct radiation vector orientated normally towards the solar beams, at the top of the atmosphere, we will have for each solar energy flux density for a horizontal surface, during a day, at this same site, the value:

$$Q = \int_{Tn}^{Tp} \left[\frac{Jo}{r^2}\right] \cos z \ \ dt \qquad (5)$$

where:

$$\cos z = sind.sinj + \cos d.\cos j.\cos H \qquad (6)$$

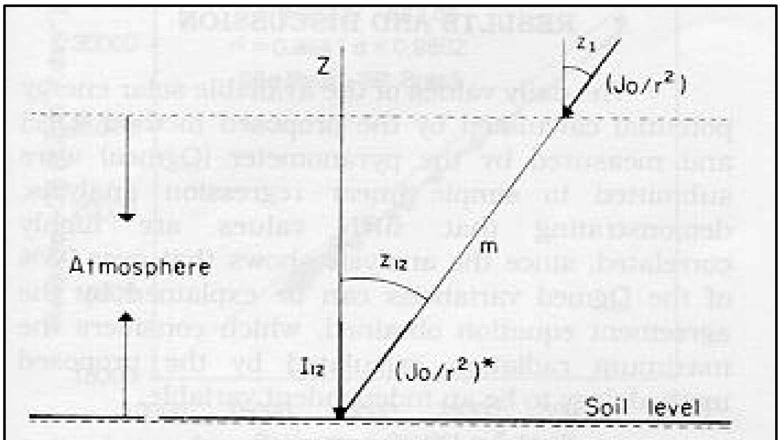

Figure 1. Schematic representation of the trajectory of solar radiation at the sun's meridian crossing.

According to Figure 1, we will have simultaneously at soil level a flux instantaneous density on a horizontal surface equivalent to $(Jo/r^2)^*$.cosz, being $(Jo/r^2)^*$ the value of difuse and direct radiation, at soil level, transmitted through a number of optical masses m of the atmosphere.

Thus, we will have as quotient Qg/Qo the following relationship:

$$\frac{Qg}{Qo} = \frac{\int_{Tn}^{Tp} \left[\frac{Jo}{r^2}\right]^* .\cos z \ \ dt}{\int_{Tn}^{Tp} \left[\frac{Jo}{r^2}\right] .\cos z \ \ dt} \qquad (7)$$

Accepting as a fundamental working hypothesis that $(Jo/r^2)^*$ can be considered roughly constant during the day, we can define that:

$$\frac{Qg}{Qo} = \frac{\left[\frac{Jo}{r^2}\right]^* \int_{Tn}^{Tp} \cos z \ \ dt}{\left[\frac{Jo}{r^2}\right] \int_{Tn}^{Tp} \cos z \ \ dt} \qquad (8)$$

Considering that the integrals are identical and can be cancelled out, we will find that:

$$\frac{Qg}{Qo} = \frac{\left[\frac{Jo}{r^2}\right]^*}{\left[\frac{Jo}{r^2}\right]} \qquad (9)$$

In the equation above the term $(Jo/r^2)^*$, at the meridian crossing (solar middle day) we will have the following approximate value:

$$\left[\frac{Jo}{r^2}\right]^* = \frac{I_{12}}{\cos z_{12}} \qquad (10)$$

Considering that, at the meridian crossing, H = 0 in the expresion which defines **z** as a function of δ, φ and H, we can obtain that:

$$\cos z = sin d . sin j + \cos d . \cos j \qquad (11)$$

Then:

$$z_{12} = d - j \qquad (12)$$

Thus:

$$\cos z_{12} = \cos(d - j) \qquad (13)$$

Therefore, we will find that:

$$\frac{Qg}{Qo} = \frac{\frac{I_{12}}{\cos z_{12}}}{\frac{Jo}{r^2}} \qquad (14)$$

$$\frac{Qg}{Qo} = \frac{I_{12}}{\left[\frac{Jo}{r^2}\right] . \cos(d - j)} \qquad (15)$$

With this equation, we have found that atmospheric transmissivity on cloudless days, defined by Qg/Qo, will be able to be estimated as a function of the measurement of solar radiation intensity at the meridian crossing (I_{12}) and the astronomical parameters Jo/r^2, δ e φ.

The value of Qg/Qo, determined this way, also expresses, according to Prescott general equation, the sum of the **a** and **b** parameters on a cloudless day, since the insolation ratio in this condition is equal to 1 (theorical value). Thus:

$$\frac{Qg}{Qo} = a + b \qquad (16)$$

Consequently, the maximum potential of incident solar radiation for a given day and site will be able to be calculated by means of the following equation:

$$Qgm = \frac{Qo.I_{12}}{\left[\frac{Jo}{r^2}\right].\cos\left(d - j\right)} \qquad (17)$$

where Qgm is the incident maximum global solar radiation on a horizontal surface on a given day and site (KJ m^{-2} day^{-1}); Qo is the incident solar radiation on a horizontal surface at the top of the atmosphere (KJ m^{-2} day^{-1}); I_{12} is the radiation maximum flux density at the meridian crossing (KJ m^{-2} min^{-1}); Jo, r, δ and φ are the astronomical parameters already defined before.

Validation of the proposed methodology

For evaluating and validation of the method in study it has been necessary to obtain data from Eppley pyranometers, whose integration provided the true value of Qgm (Qgmeasured). Sets of data observed in São Paulo, SP, Brazil, have been used for the period between 1995 and 1996. With this data, it was possible to evaluate the prediction supplied by the methodology through the correlations between the measured global radiation (Qgmea) and the estimated one (Qge), in function of statistical methods which provided the observed deviations in order to allow the confirmation and the use of the proposed theory. A series of radiation data has been used for the proposal of correction factors to the estimate model of the solar energy potential and another independent series of data was considered to confront measured and estimated values in 1:1 type graph.

Definition of a and b coefficients of Angström by means of estimated Qg/Qo ratio

Considering the latitudinal dependence of the **a** coefficient of the Ångström-Prescott equation, which was tested by GLOVER & McCULLOCH (1958), its value was defined by the following expression:

$$a = 0,29.\cos j \qquad (18)$$

The **b** coefficient was calculated by the difference between estimated Qg/Qo ratio, that represents the sum of the **a** and **b** coefficients of the equation for cloudless day conditions, and the value of **a**. Therefore, its value was expressed by:

$$b = \frac{Qg}{Qo} - 0,29.\cos j \qquad (19)$$

The calculated values of the available solar energy potential (Qge) by the proposed methodology were correlated to the measured values in Eppley pyranometers for the selected days. As the values of correlation and determination coefficients analysed separately can lead to interpretations not always suitable of the performance of the studied model, the agreement index **d** proposed by WILLMOTT et al. (1985) was also used.

In this paper a new **c** index proposed by CAMARGO & SENTELHAS (1995) was also adopted to indicate the performance of the method in study, putting together the accuracy (**r**) and exactness (**d**) indices, being defined by the multiplication between both indices.

RESULTS AND DISCUSSION

The daily values of the available solar energy potential calculated by the proposed method (Qge) and measured by the pyranometer (Qgmea) were submitted to simple linear regression analysis, demonstrating that such values are highly correlated, since the analysis shows that over 95% of the Qgmed variations can be explained by the agreement equation obtained, which considers the maximum radiation calculated by the proposed methodology to be an independent variable.

Thus, the regression equation for evaluation of the daily global solar radiation potential was the following:

$$Qgmea = 0,9733.Qge - 583,85$$

$r^2 = 0,9941 \quad n = 33$

The value of F was highly significant, revealing a convincing correlation between the measured and estimated data of solar energy potential. The test t for the linear coefficient of the regression equation has been significant for São Paulo, capital, Brazil, showing that the value of **a** is statistically different of zero.

Demonstrating that the determination ($\mathbf{r^2}$) and correlation (**r**) coefficients only bring information about the accuracy degree of the analysis and reveal nothing about its exactness, the agreement index (**d**) proposed by WILLMOTT et al (1985) was calculated, obtaining for the site in study the value of **d** equal to 0,9802.

The **c** index has assumed a value of 0,9772, showing an excelent performance, according to the interpretation criterion of the performance of mathematical models presented by CAMARGO & SENTELHAS (1995).

Such a performance, which proposes correction factors to estimate the solar energy potential can be better observed in Figure 2, in which it is possible to verify that accuracy (given by the tendency line), as well as exactness (visualized in the dispersal of the data around the 1:1 line) of the estimates have been very good, presenting values of **d** and **c** equal to 0,9802 and 0,9772, respectively, exceeding, however, values of **d** considered as satisfactory, whose inferior limit recommended by ROBINSON & HUBBARD (1990) is 0,75.

Figure 3 shows the dispersal of measured and estimated data of the daily solar energy potential around the 1:1 line, considering another independent series of data, aiming at better confirmation and validation of the proposed theory. It can hence be noted that this dispersal is relatively small, which reinforces the viability of the current methodology not only in São Paulo, SP, Brazil, seeing as such a theory dispenses the analysis of an extensive series of radiometric measurements dependent on daily integrations.

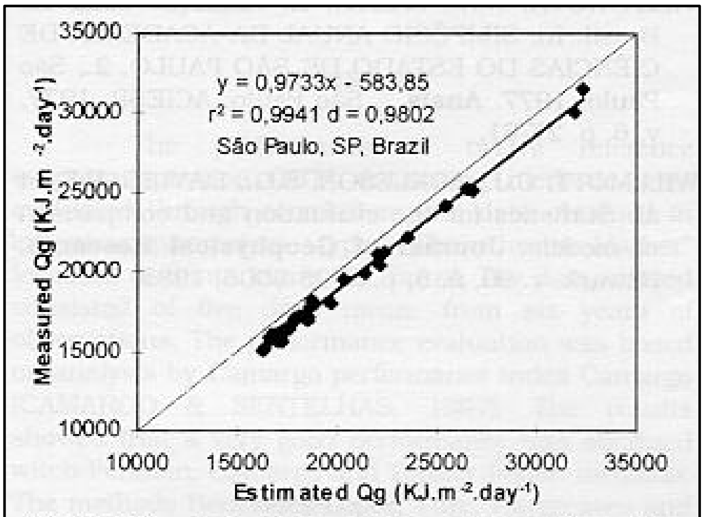

Figure 2. 1:1 type graph contrasting the solar energy potential measured by the Eppley pyranometer with the potential estimated by the proposed methodology for São Paulo, SP, Brazil;

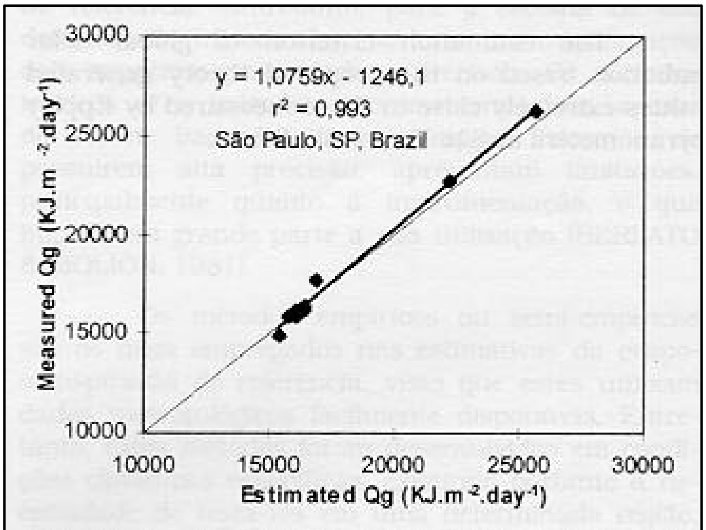

Figure 3. Comparison between measured and estimated data of solar energy potential, considering an independent series of data for São Paulo, SP, Brazil.

Concerning the proposed methodology, although the hypothesis which assumes $(Jo/r^2)^*$ as being constant throughout the day is not true, due to the fact that at elevated zenital angles the number of optical masses to be crossed over by the solar radiation beam, given by secz, determines low instantaneous values of $(Jo/r^2)^*$, it is convenient to point out that at those times a low value of cosz results in a low $(Jo/r^2)^*$.cosz product. As a result of this, the model admits that the integration of $(Jo/r^2)^*$.cosz leads to estimates close to the real values, a fact which will be able to be observed in PEREIRA (1997) at other sites considered by the author.

Figure 4, elaborated with data obtained by PEREIRA (1997), indicates that the values of **a** and **b** coefficients obtained from the methodology in study generated estimated values of global radiation extremely close to the measured data in São Paulo, capital, considering that the dispersal of the data around the 1:1 line was clearly small. This can be confirmed faced with obtainment of the following values of **d** and **c**, respectively: 0,9812 and 0,9532. Such values reinforce the use viability of the proposed methodology at above-mentioned site, being worthwhile to suggest here that such studies must be developed in many other regions of Brazil. Studies conducted in this meaning are extremely important, due to the fact that great part of the agrometeorological research (evaporation, evapotranspiration, dryness, potentials of production, etc.) leans on primarily the determination of the solar energy local input, source of all physical and biological processes reigning on the biosphere.

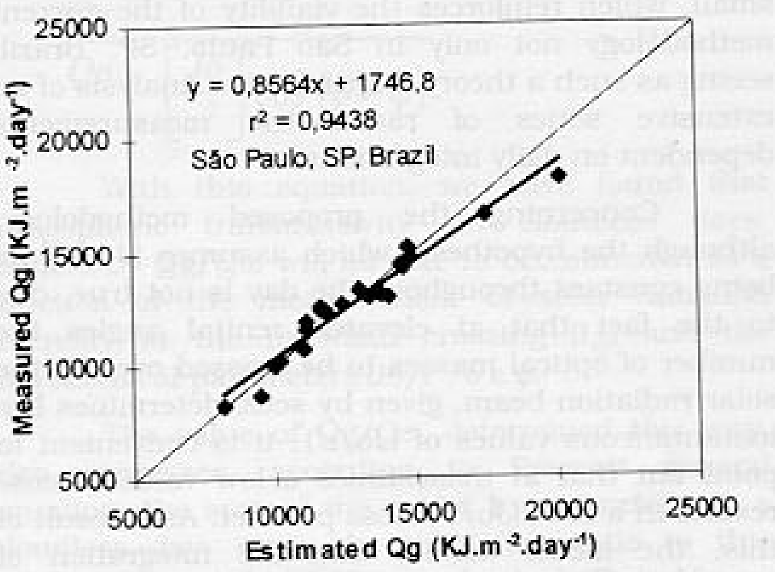

Figure 4. Comparison between the global solar radiation measured by the pyranometer and the radiation flux density estimated from the a and b coefficients of the Ångström equation proposed by the methodology in study for São Paulo, SP, Brazil.

CONCLUSIONS

It is possible to accurately estimate the maximum daily solar energy input as a funtion of only one measurement taken at the sun's meridian crossing.

The proposed methodology was efficient for evaluating the **a** and **b** parameters of the Angström equation with quickness and simplicity, eliminating the multiple error sources produced by the conventional methodology.

The estimation criterion of global solar radiation based on the proposed theory generated values extremely close to those measured by Eppley pyranometers at São Paulo, SP, Brazil.

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