Contribution to the diffuse radiation modeling in Évora, Portugal

Edgar F.M. Abreu, Paulo Canhoto and Maria João Costa
Universidade de Évora, eabreu@uevora.pt, canhoto@ uevora.pt, mjcosta@uevora.pt

Abstract - **Solar radiation data is crucial for the design of energy systems based on the solar resource. Since diffuse radiation measurements are not always available in the archive data series, either due to the inexistence of measuring equipment, shading device misplacement or missing data, models to generate these data are needed. In this work, one year of hourly and daily horizontal solar global and diffuse irradiation measurements in Évora are used to establish a new relation between the diffuse radiation and the clearness index. The proposed model includes a fitting parameter, which was adjusted through a simple optimization procedure to minimize the Least Square Error as compared to measurements. A comparison against several other fitting models presented in the literature was also carried out using the Root Mean Square Error as statistical indicator, and it was found that the present model is more accurate than the previous fitting models for the diffuse radiation data in Évora.**

Resumo - **Dados de radiação solar são cruciais para o dimensionamento de sistemas de energia baseados no recurso solar. Uma vez que medições de radiação difusa nem sempre estão disponíveis, devido à inexistência de equipamento, mal posicionamento do dispositivo de sombreamento ou ausência de medições, são necessários modelos para gerar este tipo de dados. Neste trabalho, um ano de medições horárias e diárias de radiação solar global e difusa numa superfície horizontal em Évora são usados para estabelecer uma nova relação entre a radiação difusa e o índice de claridade. O modelo proposto inclui um parâmetro de ajuste, determinado através de um processo de otimização simples com o intuito de minimizar o Erro dos Mínimos Quadrados em comparação com as medições. Foi também efetuada uma comparação com outros modelos presentes na literatura usando o Erro Quadrático Médio como indicador estatístico, mostrando que, para as medições de radiação difusa em Évora, o modelo apresentado é mais exato do que os modelos previamente apresentados na literatura.**

Key words - solar energy, solar radiation, diffuse radiation, clearness index, fitting model.

INTRODUCTION

The final overall performance of solar energy systems is highly dependent on the solar radiation data used upon their design. Historically, most of the weather stations measure only global solar radiation data although diffuse and direct solar radiation components are also important in the design of solar applications. For example, the direct normal irradiation is essential in the design of concentrating solar power plants [1], which however can be estimated from the global and diffuse irradiation data if direct measurements are not taken.

The generation of diffuse radiation data is done mostly via models obtained for several parts of the globe [2]. These models are generated on a daily or monthly mean daily basis and are classified in two main categories. In the first category, the diffuse fraction or cloudiness index (i.e. the ratio of horizontal diffuse radiation to the horizontal global solar radiation) is correlated with different input elements as the sunshine duration and/or clearness index (defined as the ratio of the horizontal global irradiance to the corresponding irradiance available at the top of the atmosphere), or cloud cover. In the second category, the diffuse coefficient or diffuse transmittance index (i.e. the ratio of horizontal diffuse radiation to the extraterrestrial solar radiation) is correlated with several input elements as the sunshine duration, clearness index or both [2]. In this work, the generation of diffuse radiation data will be studied using a model that correlates the cloudiness index with the clearness index.

The clearness index is closely correlated to the diffuse radiation, thus it has been considered as a determinant element for the estimation of diffuse radiation. The main advantage of using this type of correlation is that only measurements of global solar radiation are needed [2], which is the most widely measured component.

In this study, one year of one minute horizontal global and diffuse solar irradiance measurements, ending in March 2016, and taken with two pyranometers Kipp&Zonen, model CM6B, at Évora, Portugal [3], are used to establish a fitting model, which correlates the hourly and daily diffuse irradiation fractions with the clearness index. The proposed model is a new simple way for obtaining the diffuse data based on the clearness index. The model is compared against other fitting models presented in the literature.

LITERATURE REVIEW

Various models have been proposed in the literature for obtaining the diffuse fraction using several functional forms [2]. In the following equations, the symbols a to e represent constants. The simpler form of these models is a linear function, given by [4]-[9]:

$$K_d = a + b \cdot K_t \quad (1)$$

where K_d is the diffuse fraction (or cloudiness index) and K_t is the clearness index, given respectively by:

$$K_d = H_d \;/\; H \quad (2)$$

$$K_t = H \;/\; H_0 \quad (3)$$

where H_d is the diffuse radiation, H is the global solar radiation and H_0 is the extraterrestrial radiation, all in a horizontal plane.
Several authors used polynomial functions of second, third and fourth order for obtaining the diffuse fraction. The fourth order polynomial function is given by:

$$K_d = a + b \cdot K_t + c \cdot K_t^2 + d \cdot K_t^3 + e \cdot K_t^4 \quad (4)$$

The authors of [8], [10]-[12] used second order polynomial functions to establish the relation between cloudiness index and diffuse fraction. Third order polynomial functions were used in [1], [8], [9], [12] and [13]. Fourth order polynomial functions were used in [11], [12] and [14].
Another functional form used to generate diffuse fraction values is the sigmoid function, which was adopted by the authors of [15]-[18] and is given by:

$$K_d = a - b \cdot (1/\exp{(c - d \cdot K_t)}) \quad (5)$$

The model proposed in this study is based on the combination of two linear asymptotic functions and is described in the following section.

PROPOSED MODEL

A model for generation of hourly and daily diffuse irradiation fraction data from the cloudiness and clearness indexes is proposed based on the following general expression:

$$K_d = [1 + f(K_t)^{-N}]^{-1/N} \quad (6)$$

where $f(K_t)$ is a linear function obtained by the least square fitting of the measurements for $0.5 \le K_t \le 0.8$, thus describing asymptotically the clear sky limit, and N is the fitting parameter that adjusts the model to the measured data also in the overcast limit $K_d \rightarrow 1$ and once K_d is not higher than 1. This function is shown in Figure 1 together with the daily irradiation data while the Figure 2 shows the simple optimization procedure in order to obtain the value of N that minimizes the fitting error. The optimal value of the parameter N is 5.929 for the daily correlation and 48.589 for the hourly correlation. These values present the minimum Least Square Error (LSE).

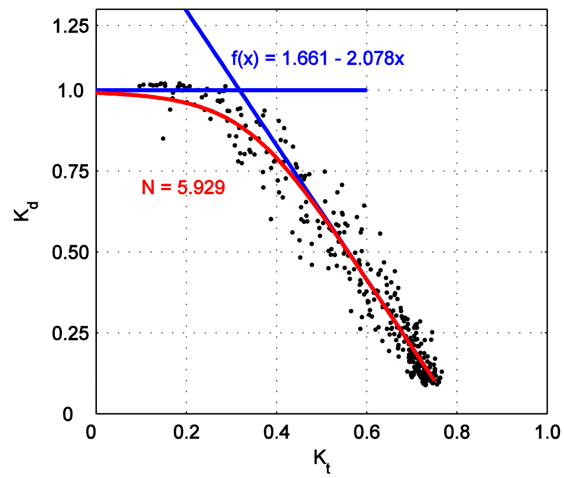

FIGURE 1
DAILY CORRELATION FOR ÉVORA.

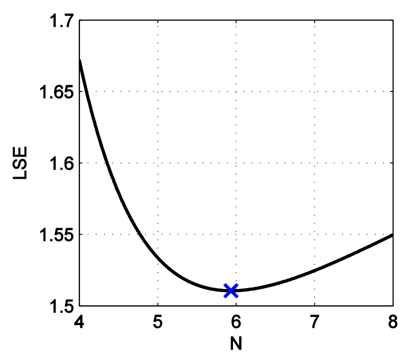

FIGURE 2
OPTIMIZATION OF THE FITTING PARAMETER N.

The correlation for the daily irradiation is given by:

$$K_d = [1 + (1.661 - 2.078 \cdot K_t)^{-5.929}]^{-1/5.929} \quad (7)$$

while for the hourly values is given by:

$$K_d = [1 + (1.502 - 1.820 \cdot K_t)^{-48.589}]^{-1/48.589} \quad (8)$$

RESULTS

The transition between the two asymptotic limits, typically in the range $0.2 \le K_t \le 0.4$, is smoother for the daily values because all the cloudiness conditions during a complete day are included, thus resulting in lower values of K_d in that range and, consequently, a lower value of the fitting parameter N is obtained. On the other hand, as distinct cloudiness conditions during a day are better resolved with the hourly data, the respective values of K_d are closer to the asymptotic limits and thus a higher value of N is found through the fitting procedure.

In order to validate the proposed model, these results were compared against several other fitting models presented in the literature for similar latitudes. The models used were the Gopinathan model [6], the Barbaro model [8], the Bortolini model [1] and the Ruiz-Arias model [15], given by (9), (10), (11) and (12), respectively. These models are valid for the latitude of Évora according to the authors. The comparison for the daily and hourly data is shown in Figure 3 and Figure 4, respectively.

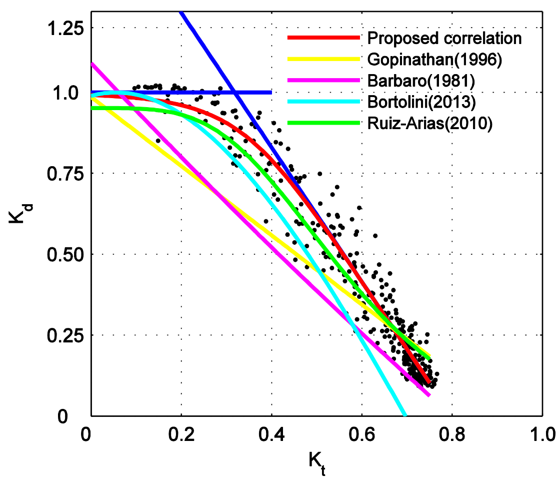

FIGURE 3
DIFFUSE INDEX AS FUNCTION OF CLEARNESS INDEX FOR DAILY DATA.

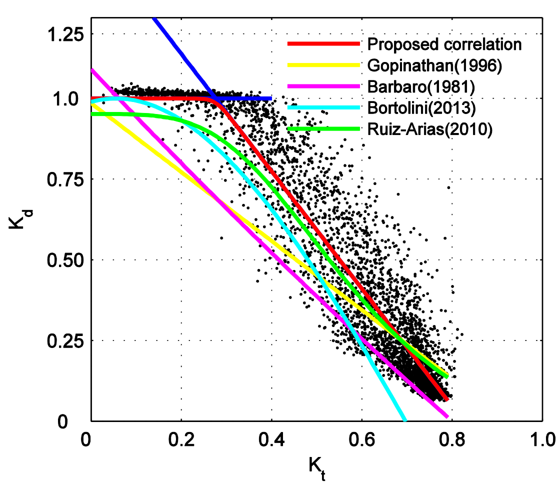

FIGURE 4
DIFFUSE INDEX AS FUNCTION OF CLEARNESS INDEX FOR HOURLY DATA.

$$K_d = 0.9851 + 1.0680 \cdot K_t \tag{9}$$

$$K_d = 1.0896 + 1.4797 \cdot K_t + 0.1471 \cdot {K_t}^2 \tag{10}$$

$$K_d = 0.9888 + 0.3950 \cdot K_t + 3.7003 \cdot K_t^2 + 1.5729 \cdot K_t^3 \tag{11}$$

$$K_d = 0.952 - 1.041 \cdot exp(-exp(2.3 - 4.702 \cdot K_t)) \tag{12}$$

The comparison between the models was done using the Least Square Error (LSE) and the Root Mean Square Error (RMSE), given by (13) and (14), respectively.

$$LSE = \sum_{i=1}^{k} (y_{i,mod} - y_{i,meas})^2 \tag{13}$$

$$RMSE = \sqrt{\frac{1}{k} \cdot \sum_{i=1}^{k} (y_{i,mod} - y_{i,meas})^2} \tag{14}$$

where $y_{i,mod}$ is the value of K_d obtained by the model for the K_t the measurement i and $y_{i,meas}$ is the value of K_d for the measured data. The LSE and the RMSE for the proposed model and for the models presented in the literature, both for the daily and hourly values, are shown in Table I and Table II, respectively.

TABLE I
LSE AND RMSE VALUES FOR THE DAILY DATA

Models	LSE	RMSE
Proposed	1.5100	0.06560
Gopinathan [6]	6.9183	0.14039
Barbaro [8]	9.6900	0.16615
Bortolini [1]	12.982	0.19232
Ruiz-Arias [15]	2.1552	0.07836

TABLE II
LSE AND RMSE VALUES FOR THE HOURLY DATA

Models	LSE	RMSE
Proposed	45.935	0.10639
Gopinathan [6]	131.04	0.17970
Barbaro [8]	168.36	0.20369
Bortolini [1]	215.75	0.23058
Ruiz-Arias [15]	57.156	0.11868

From the data from Table I and Table II it can be verified that the error of the models is higher for the hourly data and lower for the daily data. The reason for this is the dispersion of the data, which is higher when considering lower integration times. This variability greatly depends on the changing cloudiness conditions and other atmospheric elements such as the aerosols [19]. The model proposed in this study presents the minimum error for both daily and hourly data as compared with the other models, while the Ruiz-Arias [15] model also presents very good results. The

Bortolini [1] model is the model which presents higher errors.

CONCLUSIONS

In this study, a simple model was proposed to estimate the diffuse fraction using the clearness index for Évora, Portugal. The main advantages of this proposed model are its simple implementation and the need of only global solar radiation measurements to determine the diffuse fraction. The comparison against previously proposed models in the literature shows that for the data sample used, the proposed method is the one which presents minor LSE and RMSE when compared to the measured data. In future work, more years of measurements must be considered and the models presented in the literature must be fitted to the data to perform a more accurate comparison with the proposed method. Also different atmospheric conditions will be considered in order to analyze the separate and combined effect of clouds, aerosols and water vapour.

ACKNOWLEDGMENT

The authors acknowledge the funding provided by the European Union through the European Regional Development Fund, included in the COMPETE 2020 (Operational Program Competitiveness and Internationalization) through the ICT project (UID/GEO/04683/2013) with the reference POCI-01-0145-FEDER-007690 and the project DNI-Alentejo ALT20-03-0145-FEDER-000011.

REFERENCES

[1] Bortolini, M, Gamberi, M, Graziani, A, Manzini, R, Mora, C, "Multi-location model for the estimation of the horizontal daily diffuse fraction of solar radiation in Europe", *Energy Conversion and Management,* Vol 67, 2013, 208-216.

[2] Khorasanizadeh, H, Mohammadi, K, "Diffuse solar radiation on a horizontal surface: Reviewing and categorizing the empirical models", *Renewable and Suistanable Energy Reviews,* Vol 53, 2016, 338-362.

[3] Canhoto, P., "Preliminary Analysis of Irradiance Data for the Generation of a Typical Solar Radiation Year for Évora, Portugal", Technical Report, Institute of Earth Sciences, University of Evora, 2016. (http://hdl.handle.net/10174/18249)

[4] Page, J, K, "The estimation of monthly mean values of daily total short-wave radiation on vertical and inclined surfaces from sunshine records for latitudes 40N–40S", *Proceedings of UN conference on new sources of energy*, Vol 4, No. 598, 1961, 378-390.

[5] Iqbal, M, "A study of Canadian diffuse and total solar radiation data-I. Monthly average daily horizontal radiation", *Solar Energy*, Vol 22, 1979, 81-86.

[6] Gopinathan, K, K, Soler, A, "Effect of sunshine and solar declination on the computation of monthly mean daily diffuse solar radiation", *Renewable Energy*, Vol 7, No. 1, 1996, 89-93.

[7] Spitters, C, Toussaint, H, Goudriaan, J, "Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. Part I. Components of incoming radiation", *Agricultural and Forest Meteorology*, Vol 38, 1986, 217-229.

[8] Barbaro, S, Cannata, G, Coppolono, S, Leone, C, Sinagra, E, "Diffuse solar radiation statistics for Italy, *Solar Energy*, Vol 26, 1981, 429-435.

[9] Jacovides, C, P, Hadjioannou, L, Pashiardis, S, Stefanou, L, "On the diffuse fraction of daily and monthly global radiation for the island of Cyprus", *Solar Energy*, Vol 56, 1996, 565-72.

[10] Lalas, D, P, Petrakis, M, Papadopoulos, C, "Correlations for the estimation of the diffuse radiation component in Greece", *Solar Energy*, Vol 39, 1987, 455-458.

[11] Bindi, M, Miglietta, F, Zipoli, G, "Different methods for separating diffuse and direct components of solar radiation and their application in crop growth models", *Climate Research*, Vol 2, 1992, 47-54.

[12] Martinez-Lozano, J, A, Utrillas, M, P, Gomez, V, "Estimation of the diffuse irradiation from global solar radiation. Daily and monthly average daily values, *Renewable Energy*, Vol 4, 1995, 95-100.

[13] deMiguel, A, Bilbao, J, Aguiar, R, Kambezidis, H, Negro, E, "Diffuse solar irradiation model evaluation in the North Mediterranean Belt area", *Solar Energy*, Vol 70, 2001, 143-153.

[14] Collares-Pereira, M, Rabl, A, "The average distribution of solar radiatioin – correlations between diffuse and hemispherical and between daily and hourly insulation values", *Solar Energy*, Vol 22, 1979, 155-164.

[15] Ruiz-Arias, J, A, Alsamamra, H, Tovar-Pescador, J, Pozo-Vázquez, D, " Proposal of a regressive model for the hourly diffuse solar radiation under all sky conditions", *Energy Conversion and Management*, Vol 51, 2010, 881-893.

[16] Filho, E, P, M, Oliveira, A, P, Vita, W, A, Mesquita, F, L, L, Codato, G, *et al* "Global, diffuse and direct solar radiation at the surface in the city of Rio de Janeiro: Observational characterization and empirical modeling", *Renewable Energy*, Vol 91, 2016, 64-74.

[17] Oliveira, A, P, Escobedo, J, F, Machado, A, J, Soares, J, "Correlation models of diffuse solar-radiation applied to the city of São Paulo, Brazil", *Applied Energy*, Vol 71, 2002, 59-73.

[18] Boland, J, McArthur, L, C, Luther, M, "Modelling the diffuse fraction of global solar radiation on a horizontal surface", *Environmetrics*,, Vol 12, 2001, 103-116.

[19] Salgueiro, V., Costa, M.J., Silva, A.M., Bortoli, D., "Variability of the Daily-Mean Shortwave Cloud Radiative Forcing at the Surface at a Midlatitude Site in Southwestern Europe", J. Climate, Vol. 27, 2014, 7769–7780. doi: http://dx.doi.org/10.1175/JCLI-D-13-00696.1

AUTHOR INFORMATION

Edgar F.M. Abreu PhD student, University of Évora & Institute of Earth Sciences, eabreu@uevora.pt
Paulo Canhoto Universiy of Évora, Physics Department & Institute of Earth Sciences, canhoto@uevora.pt
Maria João Costa Universiy of Évora, Physics Department & Institute of Earth Sciences, mjcosta@uevora.pt