INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
A. Maraj et al., Vol.12, No.3, September, 2022

Modelling and the Experimental Validation of the Long-term Averaged Solar Radiation on a Tilted Solar Collector Facing the South-East Direction

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Received: 05.07.2022 Accepted: 16.08.2022

Abstract- The paper shows the modelling and its experimental validation of the monthly averaged daily radiation on the tilted south-east facing surface of a solar collector, which is the collecting component of a solar water heating system situated in a location utilized as the case study. The modelling is based on the general form of the "Klein and Theilacker method". To perform the calculation of the monthly averaged clearness index for the case study, one of the available models is utilized. Monthly averaged values of the ratio of total radiation on a sloped surface to that on a horizontal one are determined. Also, the monthly averaged values of daily radiation on the sloped surface are estimated. Validation of the estimated values through the application of the "Klein and Theilacker method" is performed based on recorded experimental data obtained every minute during a multi-year period. Some statistical parameters utilized in this work include the percentage error, the mean bias error, the mean percentage error, the root mean square error, and the coefficient of determination. The comparison of predicted and experimental data confirms the ability of the utilized method for the considered tilted south-east facing surface and location. It is noticed that the method slightly overestimates the measured values during the winter season.

Keywords daily total radiation, averaged values, tilted surface, Klein-Theilacker method, experimental validation.

1. Introduction

Estimating the monthly values of total radiation on plane of arrays with different slopes and various orientantions is very helpful to design and to evaluate different types of solar energy systems. Also, these values are very important to design solar energy collecting devices, structures of the buildings, etc. In general, measured data for horizontal planes are available for many locations in the world. However, measured data related to the total radiation on a specific plane with different slope and orientation are mostly not available. Many researchers have put considerable efforts in modelling, evaluating, analysing, improving, and validating the estimated solar radiation data with those obtained from the measurements.

Nowadays, the number of available solar radiation models is enormous. Many of them are used for the estimation of different parameters regarding specific regions in the world. So far, many of the solar radiation models are not validated for a great number of very densely populated areas. Their validation will be very helpful in evaluating the ability of a model to provide accurate and reliable data for surfaces with different angles and orientations utilized in many solar energy applications. With this aim, the validation of the considered model is performed by utilizing the experimental data. These data refer to a location having Mediterranean climate conditions and a particular interest for solar applications. Also, for this location is noticed a gap regarding the research works in relation to the modelling of total radiation and its experimental validation. Different solar radiation models (linear, exponential, power, etc.) related to the monthly average clearness index are provided by Maraj et al. [1]. The most accurate 6-models are evaluated and applied for the selected location. The results show that the power model 2 was the most appropriate model to represent the monthly average values for the clearness index and global solar radiation on a horizontal plane situated in the considered location.

Modelling with high accuracy the solar energy potential in different regions and climates represents a real challenge. The provided accuracy shows a significant impact in the energy and economic estimation of systems which exploit this energy source. Referring to many locations in the world, plenty of research work was focused on modelling the solar radiation on horizontal and tilted surfaces facing to the south direction. In most of these studies, hourly, daily, monthly and annual data were used.

Liu and Jordan [2] presented the first method to define the monthly average daily radiation on tilted surfaces towards the Equator.

Iqbal [3] estimated the insolation on south-facing surfaces by using hourly values of total and diffuse radiation obtained from experimental data provided in 3-meteorological stations. In addition, the author compared them with estimated data for daily insolation on a tilted surface oriented toward the equator by using the Liu and Jordan method.

In another study, Iqbal [4] calculated the ratio $\bar{R}$ for the surfaces facing due south and tilted at 50º and 90º. Here, measurement data of hourly total radiation on horizontal plane provided from 7-hydrometeorological stations in Canada were used.

Evseev and Kudish [5] utilized 11-models to convert total radiation intensities on horizontal area to that on a tilted one. Also, they compared them with data provided from measurements of total radiation for a south oriented area tilted at 40º in the location of Beer Sheva, Israel.

El-Sebaii et al. [6] used data measured for a period of 11-years for Jeddah, Saudi Arabia. They calculated the total solar radiation on a tilted area facing south direction with different tilt angles by using two models. Later, they compared the estimated data with Surface Meteorology and Solar Energy Model.

Khalil and Shaffie [7] analysed hourly data of total, direct, and diffusive solar radiation related to a horizontal area and another tilted one in Cairo, Egypt for a 10-years period. In their study, they used several models to estimate and to compare the total solar irradiation on the south-facing tilted surface.

Pandey and Katiyar [8] estimated monthly average hourly global radiation for surfaces with different slopes of 15º, 30º, 45º, and 60º facing the south direction. For this purpose, they used four solar radiation models. Furthermore, they compared the estimated values with measured ones for Lucknow, India.

Horwáth and Csoknyai [9] estimated the global solar radiation by making use of 3-models. Also, they compared estimated data with data obtained from measurements of the total radiation on an area tilted at 45º and oriented towards south direction, located in Budapest, Hungary. In this study, 8-years of data were used.

Shukla et al. [10] performed the comparison between the isotropic and anisotropic models with the aim to estimate the total radiation over an area tilted at 23º. They also compared the estimated values with measured values for Bhopal, India.

Many other valuable efforts were focused on modelling the available solar radiation on tilted surfaces with different orientation. These surfaces are not so widespread as those facing the equator, but there are many applications where the presented knowledge regarding the available solar radiation is appreciable.

Klein [11] presented a calculation method for monthly averaged values of solar radiation on sloped areas. He estimated monthly values of averaged daily radiation on an area tilted at 43º due south. Also, he preformed the comparison with values related to another area oriented 15º west of south.

The method of Liu and Jordan [2] is then extended for surfaces oriented east or west of south. Klein and Theilacker [12] presented an approach or the K-T method (Klein and Theilacker method) to calculate the average radiation on tilted surfaces with different orientations.

Liu and Jordan [13] computed the total radiation for surfaces tilted at 90º facing the south, east and west direction along the three hours next to the solar noon. Also, they compared estimated data with those obtained from measurements.

Chowdhury and Rahman [14] performed the comparison of values obtained from 4-mathematical models including the K-T method with the aim to estimate the irradiance on plane of array for three locations. They presented the characteristics for each model and their accuracy.

Gopinathan et al. [15] estimated monthly averaged daily total radiation on tilted areas with different orientations situated in 3-locations in southern part of Africa. They considered 5-different inclinations and 5-surface azimuthal angles. They utilized data obtained from measurements of the monthly averaged values of daily total radiation on a horizontal area with the Hay’s model.

Mohammadi and Khorasanizadeh [16] used long-term horizontal global solar radiation data and the K-T method for vertical surfaces with orientation of 0º, 45º and 90º situated in six cities in Iran. They estimated the amount of solar radiation received by vertically mounted solar surfaces and identified the best surface azimuthal angle for the cities.

The solar energy potential in South-East European countries is given at Ref. [17].

Assi et al. [18] predicted the total solar radiation in three cities of the United Arab Emirates by utilizing an Artificial Neural Network model.

Demirtas et al [19] predicted the solar radiation by employing meteorological data. The authors used time intervals of 10-minutes.

Furthermore, many researchers made validations of the estimated values obtained from calculations with those from measurements. The validation of data is required in many instances. For this aim, many statistical tests are available and can be employed to define the data confidence. In general, the confidence related to the data is highly dependent on the magnitude of the error.

Ma and Iqbal [20] statistically compared 3-models utilized for evaluating the total radiation on inclined areas and to recommend the most accurate one. To define the accuracy of the considered models they employed two statistical tests: RMSE (Root Mean Square Error) and MBE (Mean Bias Error). The measured data refers to surfaces having slopes 30º, 60º and 90º. They were provided for Ontario, Canada.

The MBE and the standard deviation are used by Erbs et al. [21] to indicate how closely the hourly, daily and monthly average daily diffusive correlation agrees with the measured data obtained for 4-locations.

Hay and Wardle [22] assessed the uncertainty in measurements of solar radiation for extended time period both at Vancouver and Toronto. They performed three different averaging periods: daily, weekly, and annually. They also made use of RMSE, MBE (absolute and relative), and the correlation coefficient to validate the estimated data for these cities.

Isard [23] employed MBE and RMSE to validate the predicted and measured values of total solar radiation incident upon Colorado alpine tundra.

Malik and Tamam [24] employed the relative percentage error, MPE (Mean Percentage Error), RMSE to validate several models related to diffuse radiation through the data collected during a 10-years period.

Omer [25] carried out a statistical evaluation for the predicted solar radiation which is diffuse through the relative deviation, relative percentage error, MPE, MBE, RMSE and the standard deviation. To achieve the objective, measurements of the diffusive solar radiation component on a horizontal plane during a 10-years period, are exploited.

A comparative estimation of total hourly solar radiation on a tilted surface of 50º and oriented towards the south direction is presented from Kambezidis et al [26]. Their validation was performed through the RMSE and MBE for the city of Athens.

Ertekin and Yaldiz [27] compared several models for the evaluation of the total radiation in Antalya's region (Turkey). Measurements for the total solar radiation covered a period of 6-years. The considered 26-models are validated through the following statistical error test such as MPE, MBE and RMSE and the best model is evidentiated.

Rahman [28] made use of monthly averaged daily values of total radiation and those of sunshine duration at 41 locations in Saudi Arabia. Moreover, he generated a correlation to evaluate the total radiation at locations where measurements are not available. Finally, he compared the present correlations and other models by employing MPE, RMSE, MBE, and MABE (Mean Absolute Bias Error).

A comparison among the measured data of total radiation in 8-meteorological stations in Egypt and the estimated values for a time period of 12-months has been done by Tadros [29]. For this purpose, he used the following statistical tests: RMSE, MBE, t-statistics, and absolute percentage error.

Sabziparvar and Shetaee [30] used measured data from 10-locations in West and East of Iran. They modeled the daily global solar radiation by using six methods and evaluated them through MBE, RMSE, MPE, and MABE.

Notton et al. [31] estimated the hourly global solar irradiation on tilted surfaces by using artificial neural networks. They validated their estimated values with data provided from measurements for a period of 5-years. The validation was performed through MAE, MBE, RMSE, and R^2 (Coefficient of Determination).

Pashiardis et al. [32] analysed and compared hourly longwave downward and upward irradiance measurements for two sites in Cyprus. Measurements were provided for a 3-years period and were used to validate the applied models through the MBE, RMSE, and R^2.

Al-Hajj et al. [33] proposed multi-stacking models to predict the solar radiation and performed the validation through one year data obtained from measurements.

Gairaa et al [34] validated modelled data with measured ones during three years for climate conditions of the desert area in South Algeria. They utilized MBE, MPE, and RMSE.

Nkounga et al. [35] modelled the solar radiation through a multi-layer neural network with the Levenberg-Marquardt algorithm for a location in Senegal. The validation is performed through RMSE and t-stat.

This paper presents an analysis of solar radiation data generated using the K-T method based on monthly values for a case study. Through the K-T method, monthly averaged values of the ratio between the total radiation on a tilted area to that on a horizontal one are generated. Later, monthly values of the ratio are used to evaluate the respective values of the total solar radiation on a sloped area. The validation for the estimated data is performed by exploiting measured data. The measured data refer to a time period of 3-years and to a specific location having Mediterranean climate conditions. Furthermore, a statistical analysis performed on the estimated quantities and measured ones is shown. Their validation is presented in terms of the relative percentage error, MBE, MPE, RMSE, and the coefficient of determination.

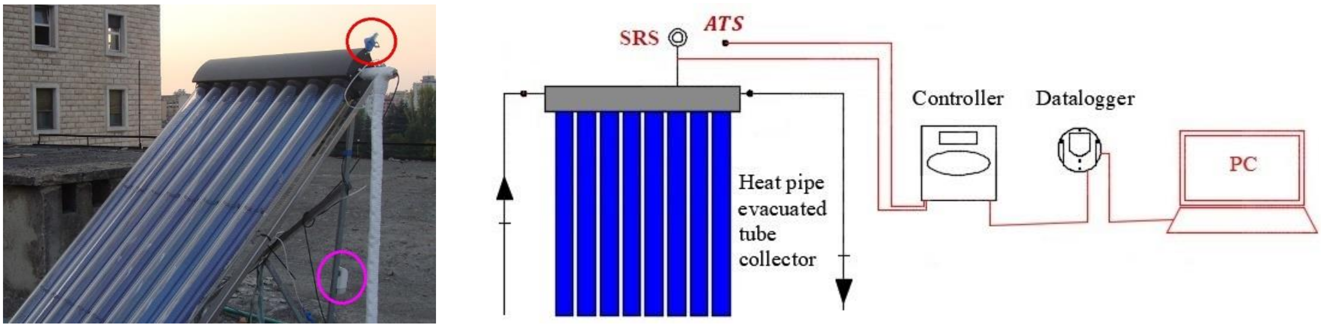
2. Materials and Methods

In this section, the site description, the input parameters, and the exploited methods are described.

2.1. Climate Site and Instrumentation

The solar irradiance collected in every minute refers to the city of Tirana, which is the capital of Albania and is situated in the central part of the country. The average altitude of the city is 110 m above the sea level and the geographical coordinates are 41.33°N and 19.82°E. The selected location has a typical Mediterranean climate and it falls at "Csa" group according to Köppen climate classification. It is characterized as hot and dry summers and mild and rainy winters [36]. Average annual sunshine hours is $\bar{n}_{annual} = 2500$ h/year [37].

Global solar irradiance on the considered tilted surface are recorded every minute for a period of 3-years. In the present work data referring to the time period between January 2011 till December 2013 are used. The measurement of global solar irradiance is realised using the sensor SRS, which is a Resol CS10 solar cell - Type E [38]. The sensor is placed on the tilted solar collector used for research purposes situated on the roof of the Faculty of Mechanical Engineering building. The measurements refers to a surface tilted 45° from horizontal and oriented 10° east of south. The selected site provides an optimum exposure of the sensor and there are no obstacles for the incoming radiation. Moreover, the sensor is calibrated at regular time intervals in accordance with the reference manual. Fig. 1 shows the sensor placement included in the layout of the system. Part of the system layout is the PT 1000 thermocouple ATS, which is a Resol FAP30. This sensor provides the measurement of the ambient air temperature for every minute. These sensors are connected to the system controller, which type is Resol DeltaSol MX.



a) b)

Fig. 1. General view (a) and the layout of the utilized sensors (b).

The collected data along the daily operation are transferred from the controller to the DL2 Datalogger and later to a personal computer (PC), for elaboration by using appropriate software.

2.2. Input Parameters

Klein [11] recommended the representative days for each month for locations with latitudes less than 65°. For the selected location, monthly averaged values for the daily total radiation on a horizontal area [37] and the sunshine hours [39] are tabulated for each month in Table 1. The value of the solar constant adopted by the World Radiation Center and used in this work is 1367 W/m^2 [40].

Table 1. Input parameters

	Representative day	Day number	$\bar{n}$ h/day	$\bar{H}$ kWh/(m^2·day)
January	17	17	4.1	1.83
February	16	47	4.4	2.468
March	16	75	5.1	3.346
April	15	105	6.8	4.468
May	15	135	8.6	5.602
June	11	162	9.9	6.477
July	17	198	11.4	6.781
August	16	228	10.6	5.99
September	15	258	8.8	4.631
October	15	288	7	3.19
November	14	318	4.2	1.981
December	10	344	2.8	1.546

2.3. Methods

The modelling is divided into two parts. In the first part, a standard method to define the diffuse component is shown, while in the second one the Klein-Theilacker method is shown.

The validation of the estimated results is performed through the use of measured values by applying several statistical test methods.

2.3.1. The Method to Define The Diffuse Component

The declination angle is determined from the equation of Cooper [41]:

$$\delta = 23.45 \cdot \sin\left[360 \cdot \frac{(284+\mathrm{n})}{365}\right] \tag{1}$$

The hour angle at sunset is determined using [42]:

$$\cos\omega_s = -\tan\phi \cdot \tan\delta \tag{2}$$

The number of daylight hours is given by [40]:

$$N = \frac{2}{15} \cdot \cos^{-1}(-\tan\phi \cdot \tan\delta) \tag{3}$$

The monthly averaged value for the daily extraterrestrial radiation over a horizontal area is given as [40]:

$$\bar{H}_0 = \frac{24}{\pi} \cdot G_{sc} \cdot \left(1 + 0.033 \cdot \cos\frac{360 \cdot n}{365}\right) \cdot \left(cos\phi \cdot \cos\delta \cdot \sin\omega_s + \frac{\pi}{180} \cdot \omega_s \cdot \sin\phi \cdot \sin\delta\right) \tag{4}$$

The monthly averaged value for the clearness index is calculated through [42]:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \tag{5}$$

For the location utilized in this work, the expression which is utilized to estimate the clearness index is provided from a previous work [1]. This model is validated by providing a very good fit and is given as:

$$\bar{K}_T = 0.3536 \cdot \left(\frac{\bar{n}}{\bar{N}}\right)^{2.336} + 0.4036 \tag{6}$$

Since the measurements of the monthly averaged values for the daily diffuse radiation are rarely available for a specific location, they must be estimated based on measurements of the averaged daily total radiation on a horizontal area. Many authors have generated different relationships for several locations. In this paper is utilized the model obtained from references [18, 40]:

$$\begin{cases} for: \quad \omega_s \leq 81.4° \; and \; 0.3 \leq \bar{K}_T \leq 0.8 \\ \frac{\bar{H}_d}{\bar{H}} = 1.391 - 3.560 \cdot \bar{K}_T + 4.189 \cdot \bar{K}_T^2 - 2.137 \cdot \bar{K}_T^3 \end{cases} \tag{7a}$$

and

$$\begin{cases} for: \quad \omega_s > 81.4° \; and \; 0.3 \leq \bar{K}_T \leq 0.8 \\ \frac{\bar{H}_d}{\bar{H}} = 1.311 - 3.022 \cdot \bar{K}_T + 3.427 \cdot \bar{K}_T^2 - 1.821 \cdot \bar{K}_T^3 \end{cases} \tag{7b}$$

2.3.2. Klein-Theilacker Method

Klein and Theilacker have developed a method that is valid for any surface azimuth angle (γ). For the case when $(\gamma \neq 0)$, the times of sunrise and sunset on the tilted surface will not be symmetrical about solar noon [12].

The ratio between the averaged value of daily total radiation on a sloped surface to that on a horizontal one for a specific month is signed by $(\bar{R})$. The expression for the ratio $(\bar{R})$ is given as [2]:

$$\bar{R} = \frac{\bar{H}_t}{\bar{H}} \tag{8}$$

Also, the value of $(\bar{R})$ can be defined as [40]:

$$\bar{R} = D + \frac{\bar{H}_d}{\bar{H}} \cdot \left(\frac{1+\cos\beta}{2}\right) + \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \tag{9}$$

The direct component of solar radiation is represented through [40]:

$$D = \begin{cases} max\big(0, \quad G(\omega_{ss}, \omega_{sr})\big) & if \; \omega_{ss} \geq \omega_{sr} \\ max(0, \quad [G(\omega_{ss}, -\omega_s) + G(\omega_s, \omega_{sr})]) & if \; \omega_{sr} > \omega_{ss} \end{cases} \tag{10}$$

where:

$$G(\omega_1, \omega_2) = \frac{1}{2 \cdot d} \cdot \left[\left(\frac{b \cdot A}{2} - a' \cdot B\right) \cdot (\omega_1 - \omega_2) \cdot \frac{\pi}{180} + (a' \cdot A - b \cdot B) \cdot (\sin\omega_1 - \sin\omega_2) - a' \cdot C \cdot (\cos\omega_1 - \cos\omega_2) + \left(\frac{b \cdot A}{2}\right) \cdot (\sin\omega_1 \cdot \cos\omega_1 - \sin\omega_2 \cdot \cos\omega_2) + \left(\frac{b \cdot C}{2}\right) \cdot (\sin^2\omega_1 - \sin^2\omega_2)\right] \tag{11}$$

$$a' = a - \frac{\bar{H}_d}{\bar{H}} \tag{12}$$

$$a = 0.409 + 0.5016 \cdot \sin(\omega_s - 60) \tag{13}$$

$$b = 0.6609 - 0.4767 \cdot \sin(\omega_s - 60) \tag{14}$$

$$d = \sin\omega_s - \frac{\pi}{180} \cdot \omega_s \cdot \cos\omega_s \tag{15}$$

The signs of (ω_{sr}) and (ω_{ss}) depend on the surface orientation [40]:

$$|\omega_{sr}| = min\left[\omega_s, \cos^{-1}\left(\frac{A \cdot B + C \cdot \sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right)\right] \tag{16a}$$

$$\omega_{sr} = \begin{cases} -|\omega_{sr}| & if \; (A > 0 \; and \; B > 0) \; or \; (A \geq B) \\ +|\omega_{sr}| & otherwise \end{cases} \tag{16b}$$

$$|\omega_{ss}| = min\left[\omega_s, \cos^{-1}\left(\frac{A \cdot B - C \cdot \sqrt{A^2 - B^2 + C^2}}{A^2 + C^2}\right)\right] \tag{17a}$$

$$\omega_{ss} = \begin{cases} +|\omega_{ss}| & if \; (A > 0 \; and \; B > 0) \; or \; (A \geq B) \\ -|\omega_{ss}| & otherwise \end{cases} \tag{17b}$$

where:

$$A = \cos\beta + \tan\phi \cdot \cos\gamma \cdot \sin\beta \tag{18}$$

$$B = \cos\omega_s \cdot \cos\beta + \tan\delta \cdot \sin\beta \cdot \cos\gamma \tag{19}$$

$$C = \frac{\sin\beta \cdot \sin\gamma}{\cos\phi} \tag{20}$$

The ground reflectance is accepted to be 0.2. This value is assumed the same for all months during which the ground is free of snow [13].

2.3.3. Comparison Techniques of Modelling

The performance of the K-T method is validated based on: (ε), (MBE), (MPE), $(RMSE)$, and (R^2).

The parameter (ε) represents the difference among the estimated and the measured values of the considered quantity in the i-th month, as a percentage of the measured value. In this case, an (ε) value close to zero is preferable. Also, a value of (ε) between ±10 % is considered acceptable and defined as:

$$\varepsilon = \frac{(\bar{H}_{Ti-m} - \bar{H}_{Ti-c})}{\bar{H}_{Ti-m}} \cdot 100\% \tag{21}$$

The (MBE) is an indicator for the average deviation of the predicted values from the measured data. A low (MBE) value is desiderable and is defined as:

$$MBE = \frac{1}{n} \cdot \sum_{i=1}^{n} (\bar{H}_{Ti-c} - \bar{H}_{Ti-m}) \tag{22}$$

The (MPE) is an indicator of accuracy, in which it usually expresses accuracy as percentage. A low value of (MPE) is desiderable and it is defined as:

$$MPE = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{(\bar{H}_{Ti-m} - \bar{H}_{Ti-c})}{\bar{H}_{Ti-m}} \cdot 100\% \tag{23}$$

The $(RMSE)$ is a measure of the variation of the predicted values around the measured data. A low value of RMSE is desiderable and it is defined as:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\bar{H}_{Ti-c} - \bar{H}_{Ti-m})^2}{n}} \tag{24}$$

The (R^2) is a measure that allows to determine how certain a prediction provided from a model is. A value of (R^2) close to the unit is desiderable. It is defined as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (\bar{H}_{Ti-c} - \bar{H}_{Ti-m})^2}{(\bar{H}_{Ti-m} - \bar{H}_{T-ave})^2} \tag{25}$$

3. Results and Discussions

In this work, the comparison between the measured and the estimated values refers to a case study. Measured values are provided from a location with typical Mediterranean climate conditions, which falls at “Csa” group. To validate the model for a south-east facing surface and a region with particular interest for solar applications, a database of measured parameters from a solar water heating system during a time period of 3-years is utilized.

The measured parameters include the tilted global irradiance and the ambient air temperature near a tilted solar collector [37]. The monthly averaged values for the daily total radiation on the horizontal plane and the monthly averaged values of daily hours of bright sunshine are provided from different publications [31, 33]. The calculated values are obtained based on the selected mathematical model. Also, the statistical evaluation of the estimated data is performed by employing several statistical test methods.

The monthly average daily extraterrestrial radiation values are given in Fig. 2. Referring to this curve, there is an increase of its values during the summer months. This was attributed to the fact that during these months the insolation is higher for northern latitude locations. Monthly averaged values for the daily extraterrestrial radiation varied between $\bar{H}_0 = (3.593 - 11.6)$ kWh/(m^2·day), where the minimum value refers to the month of December and the maximum to that of June. Referring to the annual period, the average daily extraterrestrial radiation is $\bar{H}_0^a = 7.716$ kWh/(m^2·day).

Also, the monthly average values of daily radiation referred to the horizontal plane are shown at Fig. 2. For the selected region, the values of this parameter during the summer period were higher when compared to those in the winter period. The magnitude of insolation values depends mainly on the latitude, season, and local climatic conditions. The minimum value for this parameter in the considered location is noticed in the month of December as $\bar{H}^{min} = 1.546$ kWh/(m^2·day), while the maximum in July as $\bar{H}^{max} = 6.781$ kWh/(m^2·day). Referring to the annual period, the average daily radiation on the horizontal surface is $\bar{H}^a = 4.026$ kWh/(m^2·day).

In Fig. 2, even the average monthly values of ambient air temperatures for the considered site are shown. An increase of its values during the summer months is noticed. This is attributed to the increasing effect of insolation during this period. Ambient air temperature varied in the interval between $\bar{t}_{air} = (7.9 - 28.3)$ °C, where the minimum value refers to the month of December and the maximum to that of August. Averaged annual ambient air temperature is $\bar{t}_{air} = 17.9$ °C.

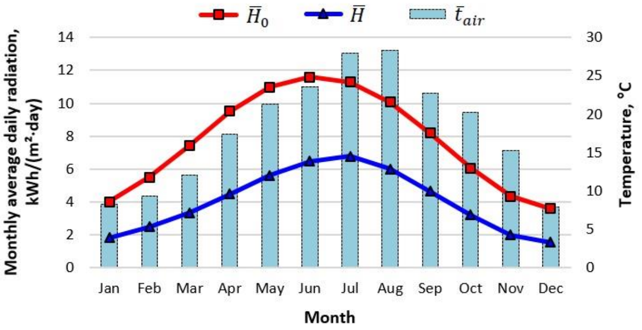


Fig. 2. Monthly mean values for $\bar{H}_0$, $\bar{H}$, and ambient air temperature.

Fig. 3 shows the monthly average clearness index $(\bar{K}_T)$, the average fraction of possible sunshine hours $\left(\frac{\bar{n}}{\bar{N}}\right)$, and the monthly fraction of solar radiation that is diffuse $\left(\frac{\bar{H}_d}{\bar{H}}\right)$.

It is noticed that the clearness index is higher during months with higher values of insolation. It varies between 0.430 in December and 0.601 in July. These values indicate the clear atmosphere of low turbidity and cloudiness during the summer period and vice versa. The annual average clearness index was 0.506.

The average fraction of possible sunshine hours also shows the same tendency. This is related to the fact that the increase in daily hours of bright sunshine $(\bar{n})$ during the summer months is higher compared to the number of daylight hours $(\bar{N})$. The minimum occurs in December (0.309), while its maximum in July (0.778). The yearly averaged fraction related to possible sunshine hours has a value of 0.561.

Regarding to the graph of the monthly fraction of solar radiation that is diffuse $\left(\frac{\bar{H}_d}{\bar{H}}\right)$, it is noticed that it fluctuates between $\left(0.3 < \frac{\bar{H}_d}{\bar{H}} < 0.4\right)$ in the summer months. While, in the months of October till May, it varies between $\left(0.4 < \frac{\bar{H}_d}{\bar{H}} < 0.5\right)$.

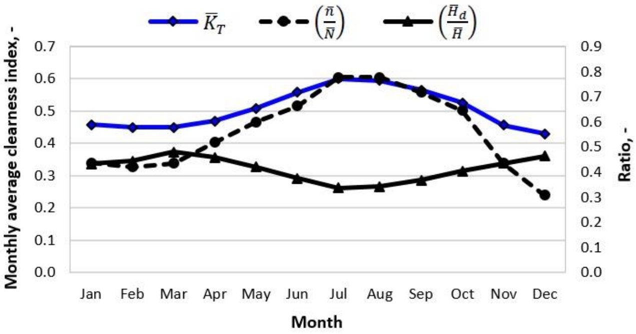


Fig. 3. Monthly average clearness index, the average fraction of possible sunshine hours, and the monthly fraction of solar radiation that is diffuse.

It is clear that the monthly fraction of solar radiation that is diffuse depends mainly from the clearness index. It is noticed that its values are lower in the months with higher values of the clearness index, or at summer months. That is attributed to the lower probable presence of clouds and thinner air mass in this period.

The maximum value is observed in March $\left(\frac{\bar{H}_d}{\bar{H}} = 0.48\right)$, while its minimum in July $\left(\frac{\bar{H}_d}{\bar{H}} = 0.337\right)$. As a conclusion, the value of the monthly fraction of solar radiation that is diffuse in the month of March is 1.423-times higher than that in the month of July. The decrease of the monthly fraction of solar radiation that is diffuse in the months of January, February and December is related to the reduced presence of the dust in the sky during the winter months (higher precipitation). This is the main reason of why the maximum value of this quantity is noticed in the month of March.

Fig. 4 shows the estimated values of the total radiation on a surface tilted 45° from horizontal and oriented 10° east of south $(\bar{H}_{T-c})$ and those for the ratio $(\bar{R})$.

For a surface having a slope of 45° and oriented 10° east of south in the selected region, it is observed that values of the total radiation on the tilted area during the summer period were higher compared to those in the winter one. Their magnitude depends mainly on the latitude, season, and local climatic conditions. The highest values ranging between $(5 < \bar{H}_{T-c} < 6)$ kWh/(m^2·day) are observed in the months from May till September. The lowest value of $(\bar{H}_{T-c} < 3)$ kWh/(m^2·day) refers to December.

The minimum value for the total radiation on the solar collector tilted plane is noticed in the month of December where $\bar{H}_{T-c}^{min} = 2.698$ kWh/(m^2·day), while the maximum in July where $\bar{H}_{T-c}^{max} = 5.910$ kWh/(m^2·day). This value is 2.19-times higher than the minimum value presenting the effect of the season and that of the weather conditions.

From the graph of the ratio $(\bar{R})$ is observed that this quantity has higher values in the time periods with lower values of insolation. It fluctuates between $(0.8531 - 1.7453)$, where the minimum occurs in June and the maximum in December.

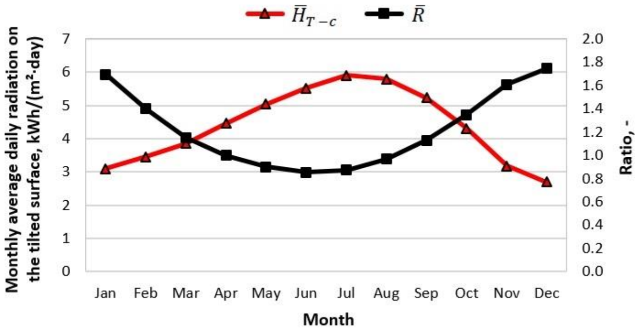


Fig. 4. Values of the radiation on the tilted plane and the ratio $(\bar{R})$.

Values of the ratio $(\bar{R} < 1)$ are observed in the months of April, May, June, July and August. This is accompanied by a reduction of the available total radiation values on the sloped area compared to those on a horizontal oriented one. However, this does not constitute a problem during the summer months where the solar radiation has higher values in the northern hemisphere. It also helps to avoid the overheating phenomenon of the solar collectors.

In the other months, the values of the ratio are $(\bar{R} > 1)$. This is accompanied with an increase in the available total radiation over the sloped area compared to the radiation on a horizontal oriented one. An increase of 74.53 % is noticed in the month of December. This positive effect is also noticed in the months where the total radiation on a tilted surface is low.

The slope (β) introduces its effect in the fluctuations of the ratio $(\bar{R})$. During the summer months, the Sun altitude is higher and it is preferred to have a low slope and vice versa. Referring to the annual time period, the estimated value of the ratio is 1.222.

Fig. 5 shows values of the total solar radiation on the sloped collector area obtained from the measurements (H_{T-m}) and the K-T method (H_{T-c}), respectively. Values obtained from measurements refer to the period from 2011 till 2013 when they were recorded. They are shown with different lines as H_{T-m}^{y1}, H_{T-m}^{y2}, and H_{T-m}^{y3}, respectively. Also, averaged values obtained from measurements during the 3-year considered time period are shown by red columns as H_{T-m}^{ave}.

The validation refers to the mean values obtained from measurements (blue columns) and the estimated ones (red columns). It is observed that there is a good match particularly in January, April, June and during the whole second part of the year. While, during February, March and May, the method doesn't provide a good fitting with the measured values. Also, the model slightly overestimates the values obtained for the winter season.

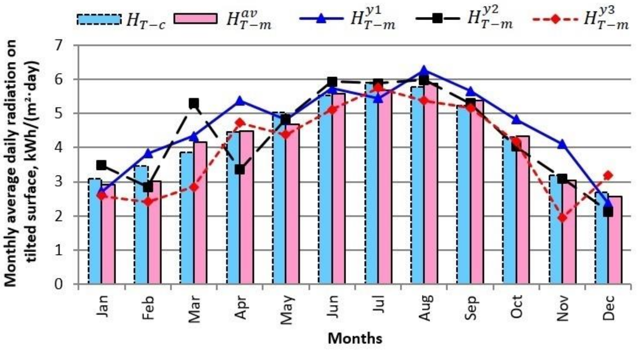


Fig. 5. Comparison between the measured, the mean, and the estimated values.

The minimum value of the relative percentage error is noticed in February where $\varepsilon_{min} = -14.226$ %, while the maximum in March where $\varepsilon_{max} = 7.401$ %.

The mean bias error is observed to be $MBE = 0.065$ kWh/(m^2·day). Referring to this value, it can be said that the K-T method slightly overestimates the calculated values compared to those measured during the 3-years period.

For the considered period a $MPE = -2.269$ %, $RMSE = 0.217$ kWh/(m^2·day) and $R^2 = 0.964$ are also obtained.

Leaning on the comparison among the measured and calculated values, it is noticed that the K-T method satisfies the 96.4 % representation of the measured values. This case study including the validation of results shows a satisfactory accuracy provided from the implementation of the Klein and Theilacker (K-T) method.

4. Conclusions

The comparison between the calculated values and measured ones related to a given location with typical Mediterranean climate conditions of “Csa” group was carried out.

Estimated values are represented as monthly averaged ones and obtained through the implementation of the K-T method for a tilted surface having a surface azimuthal angle of -10°.

Recorded data obtained every minute from the controller of a SWHS for a time period of 3-years were used. The conclusions for the location utilized in this case study are obtained as follows:

- The monthly average clearness index ranges between $\overline{K}_T = (0.430 - 0.601)$, where the maximum refers to the month of July.
- The monthly fraction of solar radiation that is diffuse fluctuates between $\frac{\overline{H}_d}{\overline{H}} = (0.337 - 0.48)$, where the minimum is noticed in the month of July.
- The ratio $(\overline{R})$ ranges between $(0.8531 - 1.7453)$, with its maximum occurring in December.
- The estimated value for the monthly averaged daily total solar radiation on a tilted area ranges between $\overline{H}_{T-c} = (2.698 - 5.910)$ kWh/(m^2·day), where the maximum value is noticed in the month of July.
- The K-T method provides a very good fit for 9-months and slightly overestimates the measured values during the winter season.
- From the comparison among the estimated values and measured ones is noticed that $\varepsilon_{min} = -14.226$ %, $\varepsilon_{max} = 7.401$ %, $MBE = 0.065$ kWh/(m^2·day), $MPE = -2.269$ %, $RMSE = 0.217$ kWh/(m^2·day), and $R^2 = 0.964$.

The results highlight the importance of this work to show the comparison among the calculated values and measured ones for the solar radiation on the tilted area of a solar collector. This case refers to a region where there is a particular interest in solar energy applications and where the gap in measured data represents a great help for utility companies. The utilized method can provide a reliable alternative for forecasting the solar radiation available on surfaces with different slopes and orientations.

Declaration of competing interest

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the financial support from the Agency for Research, Technology, and Innovation- Albania through the project “Water and Energy”. The utilized data are obtained from the controller of a solar water heating system. The trial installation was provided through this project, which included also a dissertation thesis.

Nomenclature

a - constant, -

a' - constant, -

b - constant, -

d - constant, -

A - constant, -

B - constant, -

C - constant, -

D - direct component of solar radiation, -

G_{sc} - solar constant, W/m^2

$\overline{H}$ - monthly average daily total radiation on a horizontal surface, kWh/(m^2·day)

$\overline{H}_0$ - monthly average daily extraterrestrial radiation on a horizontal surface, kWh/(m^2·day)

$\overline{H}_d$ - monthly average daily diffuse solar radiation, kWh/(m^2·day)

$\frac{\overline{H}_d}{\overline{H}}$ - monthly fraction of solar radiation that is diffuse, -

$\overline{H}_T$ - monthly average daily total radiation on the tilted surface, kWh/(m^2·day)

$\bar{H}_{T-ave}$- averaged value of $\bar{H}_T$, kWh/(m^2·day)

$\bar{H}_{Ti-m}$ - measured value of $\bar{H}_T$, kWh/(m^2·day)

H_{T-m}^{yi} - measured value of $\bar{H}_T$ for the year i, kWh/(m^2·day)

H_{T-m}^{ave} – averaged value of measured of $\bar{H}_T$, kWh/(m^2·day)

$\bar{H}_{Ti-c}$ - calculated value of $\bar{H}_T$, kWh/(m^2·day)

$\bar{K}_T$ - monthly average clearness index, -

n - day of the year, and/or number of the month, -

$\bar{n}$- monthly average daily hours of bright sunshine, h/day

$\bar{N}$- monthly average number of daylight hours, h/day

MBE - mean bias error, kWh/(m^2·day)

MPE - mean percentage error, %

$RMSE$ - root mean square error, kWh/(m^2·day)

$\bar{R}$ - ratio of total radiation on the tilted surface to that on the horizontal surface, -

R^2 - coefficient of determination, -

H_T^{max} - maximum monthly value of irradiation on solar collector plane, kWh/(m^2·month)

H_T^{min} - minimum monthly value of irradiation on solar collector plane, kWh/(m^2·month)

$\bar{t}_{air}$ - mean monthly ambient air temperature, °C

Greek symbols

β - slope of the surface, º

δ - declination angle, º

ε - percentage error, %

ρ_g - ground reflectance, º

π - constant, -

ϕ - geographical latitude, º

γ - surface azimuth angle, º

max - maximum, -

ω_s - sunset hour angle, º

ω_{sr} - sunrise hour angle on the tilted surface, º

ω_{ss} - sunset hour angle on the tilted surface, º

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