Advances in Research

17(3): 1-16, 2018; Article no.AIR.44629
ISSN: 2348-0394, NLM ID: 101666096

Comparative Analysis of Solar Radiation Characteristics in Continental Climatic Zone by Using Insolation Models

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Authors' contributions

This work was carried out in collaboration between both authors. Author FB designed the study, performed the analysis and wrote the first draft of the manuscript. Author LSS commented the analyses of the study, wrote the final draft of the manuscript and edited it. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AIR/2018/44629
Editor(s):
(1) Dr. Zakaria Boumerzoug, Professor, Department of Mechanical Engineering, University of Biskra, Biskra, Algeria.
Reviewers:
(1) Abhisak Sharma, Panipat Institute of Engineering and Technology, India.
(2) Akinnawo Olumide Olufemi , Crawford University, Nigeria.
(3) Bankole Adebanji, Ekiti State University, Nigeria.
Complete Peer review History: http://www.sciencedomain.org/review-history/27251

Original Research Article

Received 20 August 2018
Accepted 08 November 2018
Published 16 November 2018

ABSTRACT

Solar energy keeps increasing its potential to replace conventional sources of energy. However, the need for initial investment requires careful planning and efficient use of financial resources. The most vital part of such in-depth analysis is dependable data. Solar radiation values are of great significance to be able to estimate the potential of solar systems. On the other hand, solar radiation measurements are very limited in global scale. Thus, many models have been proposed to satisfy the need for the missing data. However, these models are dependent on the specifics of the region to be examined. Climatic conditions play a significant role in model development. There are four climatic regions in Turkey and each of them needs to be studied on its own. In this study, in order to design PV system for maximum efficiency under certain climatic conditions in Turkey, a comparative analysis of solar energy potential for two cities in the continental climatic zone is conducted. Solar radiation values on inclined and horizontal surfaces are

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calculated through MATLAB software. Based on the calculations, the values of the indicators show that potential for photovoltaic systems in both cities corresponds to expected levels. The solar radiation levels are evaluated to be at acceptable efficiency levels to design a photovoltaic system.

Keywords: Photovoltaic systems; solar energy; panel efficiency; renewable energy; data analysis.

1. INTRODUCTION

Adoption of solar energy is vital to meet the growing energy demand worldwide. The fact that share of carbon-based fuels in energy supply needs to be reduced due to the environmental concerns, intensify the research efforts on solar energy as one of the most significant alternatives. Its ability to reduce environmental side-effects and relatively simple technology help increase the popularity among other sources of renewable energy.

Fig. 1 displays the renewable energy distribution of the world [1]. The figure indicates that the most widely utilized renewable energy resource is hydropower while solar PV technology has not yet reached up to its potential and mainly used by developed countries to a great extent. Fig. 2 shows solar radiation received on the earth. In this figure, PW is 10 15 Watts (PetaWatt) [2]. The figure shows that only 89 PW of the 174 PW solar is absorbed by the land and oceans and available for solar energy production.

Global net radiation map is displayed in Fig. 3 [3].

Measuring solar radiation which shows the energy radiated from the sun is a significant indicator of true potential of solar energy. Lack of meteorological stations raises the need for estimation models to assess the feasibility of solar energy investments. There is a wide range of deterministic models that have been developed for this purpose. In order to evaluate and compare the appropriateness of selected provinces in the second climatic region for solar investments, a selection of these models is utilized in this study as discussed in the following section.

Fig. 1. Renewable energy distribution in the world [1]

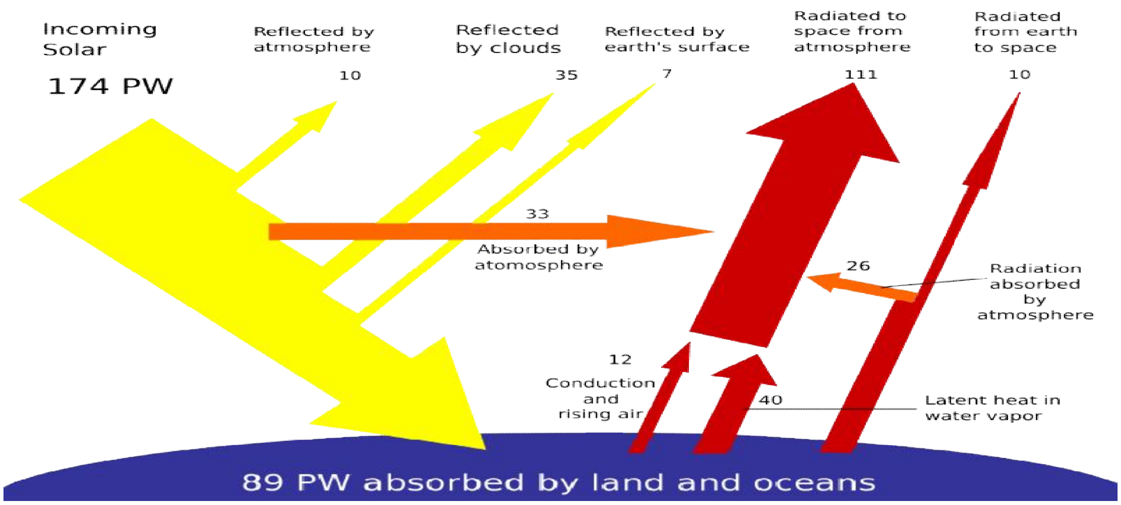


Fig. 2. Solar radiation received on the earth [2]

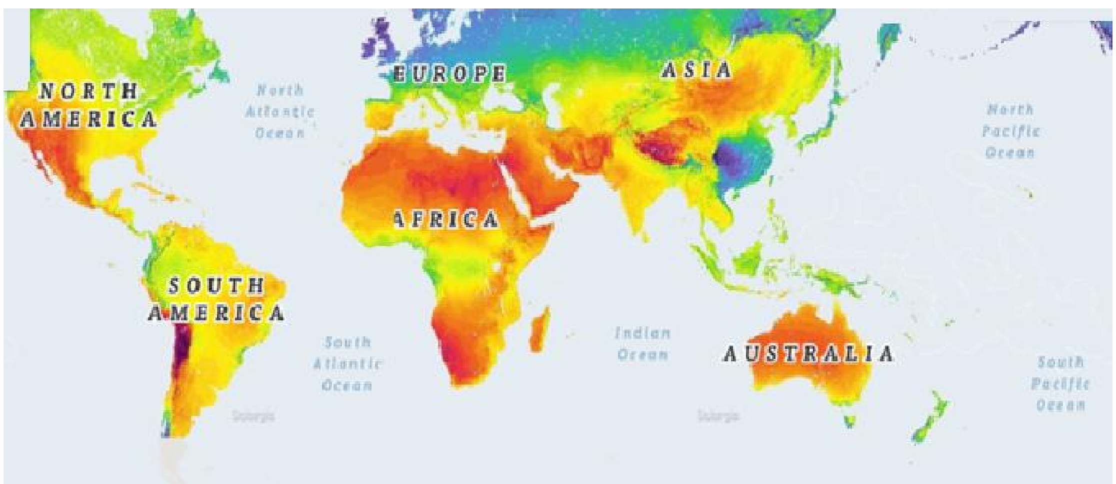


Fig. 3. Global net solar radiation map [3]

In recent years, researchers have begun to focus on the evolution for local solar radiation related to model at photovoltaic system design. Many articles also pointed out that the artificial neural network methodology is better than empiric models [4-6]. For four stations, Li et al. assessed eight sunshine duration fraction models in China. For calibration, data for eleven years are used. Four years of data are used for validation. The root means square error (RMSE) is used as a statistical indicator. RMSE of linear model changed from 1.26 to 0.72 MJ/m^{2}day. RMSE of the eight models changed from 1.33 to 0.7 MJ/m^{2}day [7]. Tang et al. studied a hybrid model fixed by Koike and Yang for the prediction of daily solar radiation [8]. For ninety-seven meteorological stations in China, the obtained irradiation data from 1993 to 2000 were used to confirm the hybrid model. The root means square error determined 0.7 and 1.3 MJ/m^{2}day, respectively [9]. To predict average hourly sun irradiation, Janjai et al. obtained a satellite-based model. For hours, the relative root means square error during the period between 3:00 pm and 9:00 am varied from 10.7% to 7.5% [10]. For 17 cities in Iran, Behrang et al. searched eleven models by applying particle swarm optimization technique [11]. For two sites in Iran, Jamshid et al. researched three sunshine duration fraction (SDF) models one modified sunshine duration fraction model. They used the method of support vector regression. The minimum and maximum temperature, relative humidity, and sunshine duration selected as inputs for kernel function

[12]. For 79 sites in China with data for 10 years, Li et al. (2010) applied a combined model (sine and cosine functions) [13]. Yadav and Chandel searched numerous articles that used ANN for the estimation of sun irradiation in three reviews and predict sun irradiation on horizontal surfaces. They pointed out that artificial neural network models were better than empiric models [14].

Zang et al. used the same method after reducing two coefficients for 35 sites in China and obtained mean absolute percentage error and RMSE ranged from 16.22%, to 4.33% and from1.88 to 1.10 MJ/m^{2}day respectively [15]. For seven sites in Spain, Almorox et al. researched eight non-sunshine duration models which were primarily based on the minimum and maximum temperature. In some models, the characteristics of latitude, altitude, mean temperature, and the day of the year were involved [16]. For four sites in Tunisia, Chelbi et al. researched five empiric models [17]. For six provinces in Iran, Khorasanizadeh et al. assessed 11 models in 3 categories for the prediction of average monthly global sun irradiation. In mean sunshine duration fraction models, the relative humidity and temperature are added as parameters [18]. Wan Nik et al. analyzed 6 mathematical expressions of the hourly solar radiation’s ratio to daily radiation. For monthly average hourly irradiation, the prediction was made [19]. For seven locations in Turkey, Düzen and Aydın investigated five sunshine duration fraction models to predict monthly average radiation [20]. For 9 sites in China, Zhao et al. researched the linear model. RMSE varied between 1.72 and 5.24 MJ/m^{2}day [21]. For Dezful, Iran, Behrang et al. investigated multi-layer perceptron network and radial basis function network. Six combinations of the parameters (wind speed, relative humidity, day number, evaporation, sunshine duration, and mean air temperature) were used. To train the models, 1398 days were used. For testing, 214 days were used [22]. For Shanghai in China, Yao et al. evaluated eighty-nine monthly average radiation models. Using various coefficients, many models are applied with the same mathematical expressions. For five sunshine duration fraction models in Shanghai, they derived new fitting coefficients [23]. For 4 sites in Thailand and 5 sites in Cambodian, Janjai et al. researched a satellite-based model. The root means square error is obtained as 1.13 MJ/m^{2}day [24]. For twenty-two sites in South Korea, Park et al. searched linear empiric model [25]. El-Sebaii et al. and El-Sebaii et al. performed three mean SDF models, three SDF models and NSDF for the prediction of average monthly global sun irradiation for Saudi Arabia. The characteristics grouped in mean sunshine duration fraction models were cloud cover, temperature, and relative humidity. To derive novel empirical coefficient values, the data of nine years are employed. RMSE of the 9 models ranged between 0.02 and 0.15 MJ/m^{2}day [26,27]. To predict hourly solar irradiation, Shamim et al. used a fixed technique. To obtain the relative humidity and air pressure, they used a mesoscale meteorological model for diverse atmospheric layers. By using available measured data, they computed the cloud cover index with relative humidity and air pressure [28]. For four provinces in Turkey, Teke and Yildirim researched cubic, linear, and quadratic empiric models [29]. Bakirci investigated sixty empiric models developed for the prediction of global monthly with average daily sun irradiation, in which many of the predictions had same formulas just with diverse regressive constant parameters [30]. For Turkey, Ozgoren et al. used the artificial neural networks model of multi non-linear regression to obtain the best independent characteristics for input layer. They selected 10 characteristics (soil temperature, month of the year, altitude, sunshine duration, cloudiness, minimum and maximum atmospheric, mean atmospheric temperature, latitude, and wind speed). Levenberg-Marquardt optimization algorithm was utilized to train the ANN [31]. For eleven meteorological sites on Tibetan, Pan et al. investigated the exponential model based on temperature. The temperature difference is used as input. To calibrate the model, data for 35 years were applied. For testing, data for 5 years were applied. RMSE of the model changed from 2.54 to 3.24 MJ/m^{2}day for all stations [32]. For twenty five sites in Spain, Manzano et al. assessed the linear Angstrom–Prescott model. More than 10 years of data were used for calibration purposes. Except for 4 sites, RMSE changed between 0.8 and 0.36 MJ/m^{2}day [33]. Kadir studied seven different sunshine duration fraction models with data measured from 18 sites in Turkey. Various models including exponential, logarithmic, quadratic, and linear equations were used for the prediction of long-term average daily global solar radiation on monthly basis. For the same sites, the performances of the applied models are obtained with slight differences [34]. For Yazd in Iran, Fariba et al. analyzed the cloud-based model and Hargreaves model. The data for sixteen years are utilized to obtain empiric constants [35]. For Gaize in Tibetan, Liu et al. investigated 3 non-sunshine duration models, 2 SDF models and 3 modified SDF models. For calibration, 1085 days of data were analyzed while 701 days of data were used for validation purposes. Root mean square error varied from 1.68 to 3.13 MJ/m^{2}day. For various seasons, they argued that deriving coefficient values respectively was unnecessary [36]. For 4 cities in India, Katiyar et al. searched the quadratic, cubic, and linear models for the prediction of monthly average radiation using annual data. The values ranged from 0.8 to 0.43 MJ/m^{2}day [37]. To predict sun irradiation, Sun et al. assessed the influence of autoregressive moving average model. They investigated the data of 20 years from 2 sites in China [38]. In a year, Ayodele et al. performed a function to present the clearness index's distribution. By using 7 years, the coefficient values determined daily sun irradiation data [39]. For Iseyin in Nigeria, Lanre et al. used the adaptive neuro-fuzzy inference system and ANN. Maximum and minimum temperature and sunshine duration were used as inputs. Data of 6 years were obtained for model training while data of 15 years were obtained to test the model. In testing and training phases, RMSE varied between 1.76 and 1.09 MJ/m^{2}day, respectively [40]. Iranna et al. investigated sixteen non-sunshine duration models to predict monthly average clearness values. As inputs, the moisture, wind speed, altitude, longitude, relative humidity, and five other temperature related characteristics are used. Data for 875 sites are evaluated to analyze the models [41]. To obtain the most effecting input characteristics for prediction, Yadav et al. [42,43] performed the Waikato Environment's software. They determined the minimum and maximum temperature, average temperature, sunshine duration, and altitude as input characteristics, while longitude and latitude were reported to be the least effective characteristics. By the artificial neural networks, the maximum mean absolute percentage error is obtained as 6.89%. Senkal proposed an artificial neural network model using altitude, longitude, latitude, land surface temperature and two diverse surface emissivity as inputs. The last 3 characteristics were determined using satellite data. To train the artificial neural networks, one year of data from ten sites is used [44]. For 4 provinces in Iran, Khorasanizadeh et al. analyzed 6 models [45]. The first model is based on exponential, the second on polynomial and other four models on cosine and sine functions. For Akure in Nigeria, Adaramola searched six non-sunshine duration models to predict long-term monthly average sun irradiation and Angstrom-Page model. In non-sunshine duration models, precipitation, relative humidity, and ambient temperature were used [46]. Jiang et al. performed to prior association rules and Pearson correlation coefficients to choose the relevant input characteristics. The wind speed, total average opaque sky cover, precipitation, opaque sky cover, minimum and maximum temperature, average temperature, relative humidity, daylight temperature, heating and cooling degree days were chosen as parameters [47]. Qin et al. used Levenberg-Marquardt algorithm with inputs including area temperature difference between night and daytime, air pressure rate number of days, vegetation index, mean area temperature, and monthly precipitation [48]. For Shiraz in Iran, Shamshirband et al. used the artificial neural network and extreme learning machine algorithm. The relative humidity, average air temperature, temperature difference, and sunshine duration fraction are applied as inputs [49]. For twelve provinces in Turkey, Senkal et al. studied artificial neural networks model. The mean beam radiation, mean diffuse radiation, altitude, longitude, and latitude were utilized as inputs. The satellite-based method for the prediction of average monthly irradiation is proposed. Root mean square error changed from 2.75 and 2.32 MJ/m^{2}day [50]. For Saudi Arabia, Mohandes applied particle swarm optimization for the training of the ANN. The longitude, altitude, latitude, sunshine duration, and month of the year were used as inputs. However, the prediction was for monthly average global sun irradiation. To train the artificial neural networks, thirty one sites' data are utilized [51].

1.1 Climate, Solar Energy Potential and Electric Production in Usak and Tokat

Equipment limitations and their high maintenance cost, have also limited the number of stations measuring solar radiation, thus meteorological variables are commonly being used in the calculation of solar radiation [52-54]. The land and sunshine period are of great significance for facilities to be established based on solar energy. Thus, comprehensive investigation needs to be undertaken about climate, solar energy potential and current facilities. Among the many models that have been developed to calculate the amount of solar radiation, sunshine hours is the most widely utilized parameter [55].

As presented in Fig. 4, more than half of Turkey possesses high potential of sunshine. Based on the study of General Directorate of Electrical

Power Resources (EIE), average annual sunshine duration of Turkey is reported to be 2640 hours (7.2 hours/day) and average radiation intensity to be 1311 kWh/m²-year (3.6 kWh/m²/day). Solar radiation maps for Usak and Tokat is displayed in Fig. 5.

In terms of solar energy potential, both cities are placed in the same climatic region. Average solar radiation, radiation function frequency, radiation function phase shift, and latitude values for both cities are presented in Table 1.

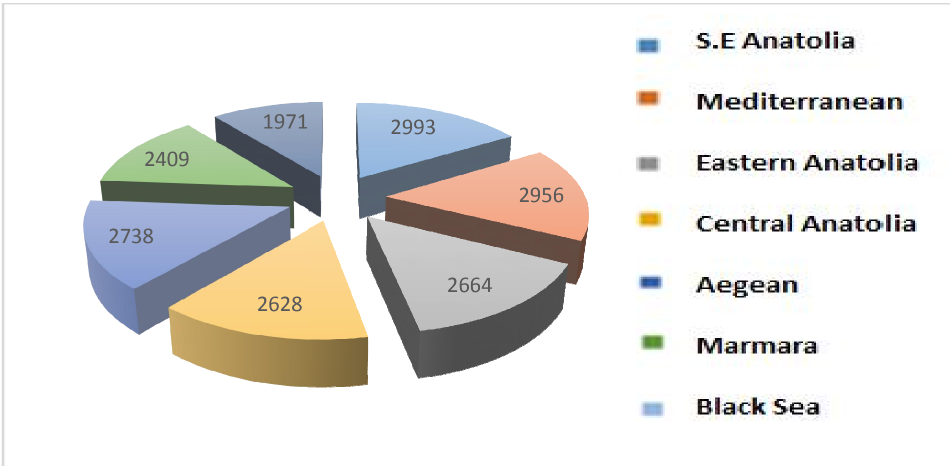


Fig. 4. Annual total solar energy period (hour-year)

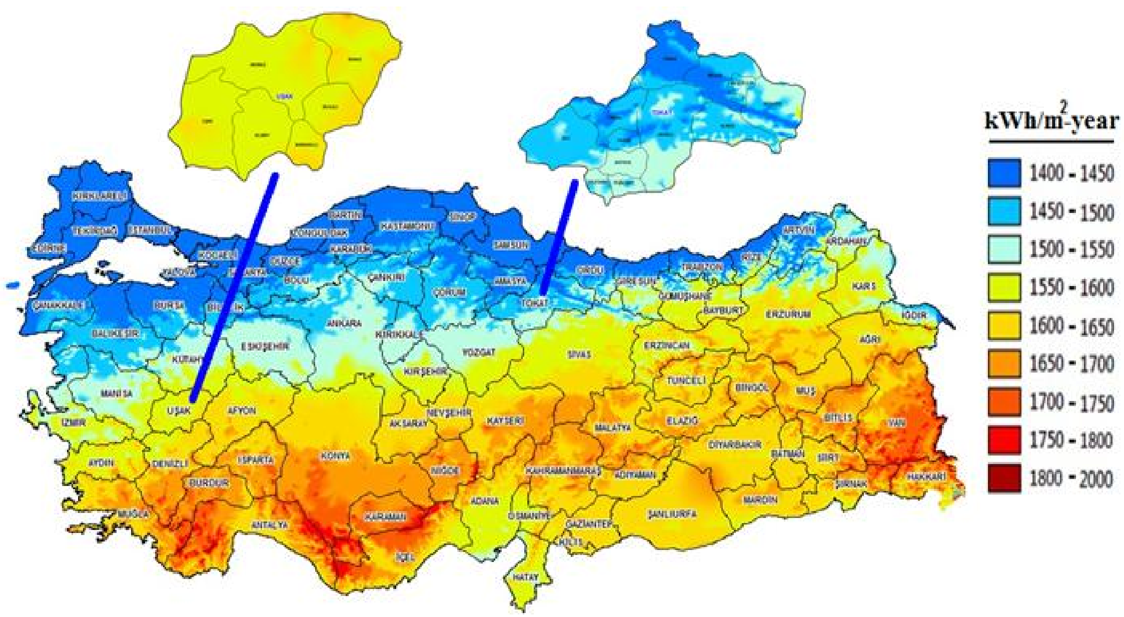


Fig. 5. Solar radiation maps for Uşak and Tokat

Table 1. Radiation values

City	Iort (MJ/m^2 .day)	FGI (MJ/m^2 .day)	FKI	Latitude
Usak	11.5	6.15	3.15	38.40
Tokat	12.5	7.76	6.19	40.00

FKI: radiation function phase shift, FGI: radiation function frequency, I_{ort}: annual average of daily total radiation

In the next section, a comparative analysis is conducted on Matlab platform for both cities to reveal their solar radiation characteristics and potential.

2. SOLAR RADIATION INTENSITY CALCULATION

Due to the climatic variations and geographic conditions, calculating amount of solar radiation depends on the specific region and requires the selection of the best model among others that are available in the literature. The model developed by Angstrom using radiation data and sunshine duration is the most commonly used one. Vartiainen et al. have proposed a statistical model to estimate the solar radiation amount through the use of data obtained from satellite [56]. Menges et al. provided a statistical comparison of daily total solar radiation on a horizontal surface in a specific city of Turkey with 50 different models in the literature [57]. Katiyar and Pandev have used solar radiation data from five different regions of India between 2001 and 2005 [58]. Consequently, they have developed Angstrom-type first, second, and third-degree solar radiation models specific for each region. Monthly total radiation values of the developed model and measured values have also been compared.

2.1 Horizontal Surface

2.1.1 Daily total solar radiation

Total solar radiation on horizontal surfaces on a given day can be calculated through the below equation [59]:

$$I = I_{ort} - FGI\cos\left[\frac{2\pi}{365}\left(n + FKI\right)\right] \quad (1)$$

where

n: days,
I: Total solar radiation,
FKI: radiation function phase shift,
FGI: radiation function frequency, and
I_t: annual average of daily total radiation.

2.1.2 Daily diffuse solar radiation

Total daily diffuse solar radiation on horizontal surfaces can be obtained using equation 2 [60].

$$I_y = I_0\,(1-B)^2\,(1+3B^2) \quad (2)$$

where,

I_o: Momentary total solar radiation,
B: Transparency index.

2.1.3 Momentary total solar radiation

Momentary total solar radiation on horizontal surfaces can be obtained using equation 2 [61,62].

$$I_o = \frac{24}{\pi} I_s \left(Cos(e)Cos(d)Sin(w_s) + w_s \cdot Sin(e)\sin(d)\right) f \quad (3)$$

where;

I_s (W/m^2): solar constant, e: latitude angle, wa_s: sunrise hour angle, f: solar constant correction factor, d: declination angle can be calculated using the related tables and equations.

Out-of-atmosphere radiation can be calculated using equation 4 [60].

$$I_{ts} = A_{ts} Cos\left[\frac{\pi}{t_{gi}}(t-12)\right] \quad (4)$$

where;

A_{ts}: solar radiation,
t_{gi}, : imaginary day length,
t: real day length

2.1.4 Momentary diffuse and direct solar radiation

Amount of momentary diffuse and direct solar radiation on horizontal surfaces can be obtained using equations 5 and 6 [21,22] where A_{ys} is function frequency.

$$I_{ys} = A_{ys} C\text{os}\left[\frac{\pi}{t_g}(t-12)\right] \quad (5)$$

$$I_{ds} = I_{ts} = I_{ys} \quad (6)$$

where;

I_{ts} = Total momentary radiation
I_{ds} = Daily radiation
I_{ys} = Momentary diffuse radiation

2.2 Calculating Solar Radiation Intensity on Inclined Surface

2.2.1 Momentary direct solar radiation

Momentary direct solar radiation on inclined surfaces (30°-60°-90° angles) can be calculated using the equation below [62].

$$I_{be} = I_b R_b \tag{7}$$

$$R_b = \frac{Cos\,\theta}{Cos\,\theta_z} \tag{8}$$

$$\cos\theta_z = \sin d \sin e + \cos d \cos e \cos w \tag{9}$$

$$\cos\theta = \sin d \sin(e-\beta) + \cos d \cos(e-\beta)\cos w \tag{10}$$

2.2.2 Momentary diffuse solar radiation

Value of momentary diffuse radiation on inclined surfaces can be obtained using the equation below [22].

$$I_{ye} = R_y I_{ys} \tag{11}$$

Conversion factor R_y for diffuse radiation can be calculated using equation below [62]:

$$R_y = \frac{1+\cos(a)}{2} \tag{12}$$

R_y parameter provides the slope of the surface. For vertical surface ($a=90^0$), R_y value is 0.5. This way, momentary values of diffuse radiation on inclined surfaces with 30°, 60°, 90° angles for 24-hour time period can be calculated.

2.2.3 Reflecting momentary solar radiation

Reflecting radiation on inclined surfaces [62] can be calculated using the equation below:

$$I_{ya} = I_{ts} p \frac{1+\cos(a)}{2} \tag{13}$$

Environment reflection rate is shown with ρ parameter and used with average value of ρ = 0.2 in calculations.

2.2.4 Total momentary solar radiation

Momentary total radiation on inclined surfaces [62] can be obtained using the equation below:

$$I_t = I_{de} + I_{ye} + I_{ya} \tag{14}$$

3. METHODOLOGY

Fig. 6 provides the values of; (a) change in annual momentary total solar radiation values for 24-hour time period, (b) change in annual momentary diffuse solar radiation values per hour, (c) change in annual momentary direct solar radiation values for a 24-hour time period on horizontal surfaces.

Fig. 7 provides daily changes of; (a) total solar radiation values per day, (b) declination angle, (c) hourly angle for sunrise, (d) solar constant for correction factor, (e) solar radiation values out of atmosphere, (f) graph of function frequency (Ays), (g) diffuse solar radiation (Ats), (h) transparency index (B) for a horizontal surface.

Momentary direct radiation values with three different angles (30^0, 60^0 and 90^0) for 24-hour time period are provided in Fig. 8. The highest values for all three angles are obtained on the 355th day at 12:00, while the lowest values are obtained on the same day at 03:00.

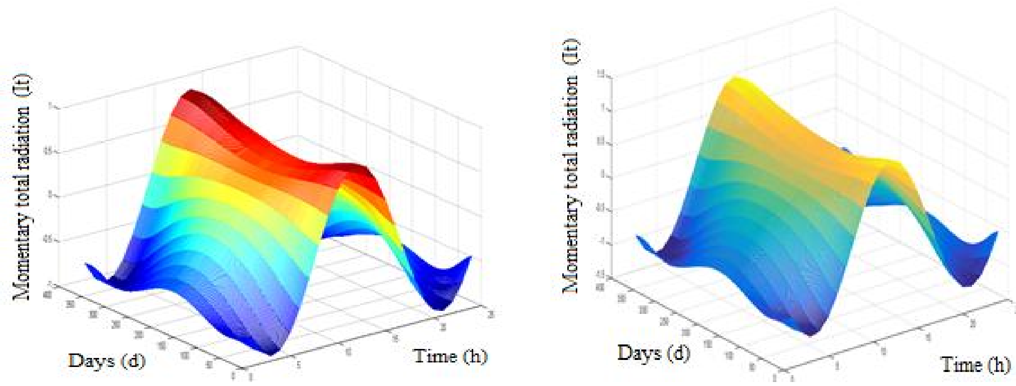
Annual momentary diffuse radiation values for three angles (30^0, 60^0 and 90^0) are provided in Fig. 9. Annual values of total momentary solar radiation for 24-hour periods are provided in Fig. 10.

4. RESULTS AND DISCUSSION

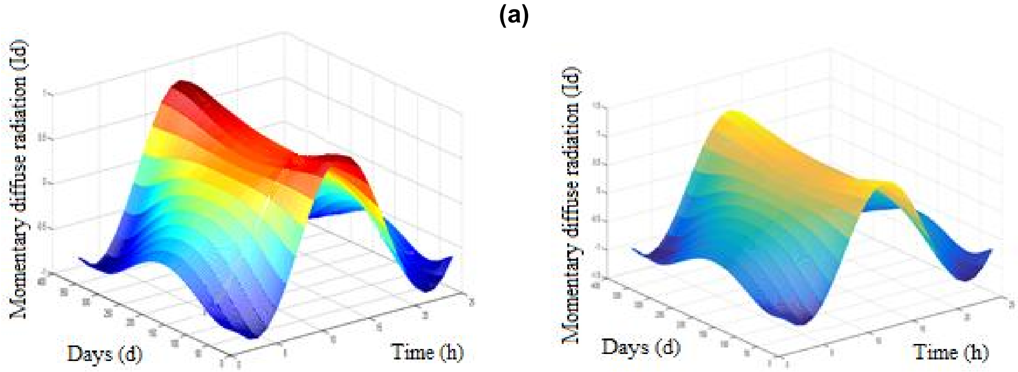
Based on the above analysis, the true potential of both cities can be evaluated through the solar characteristics calculations provided in Table 2. The values that are used in the analysis are obtained from the real values obtained from meteorology satellites.

Table 2. Solar radiation attributes

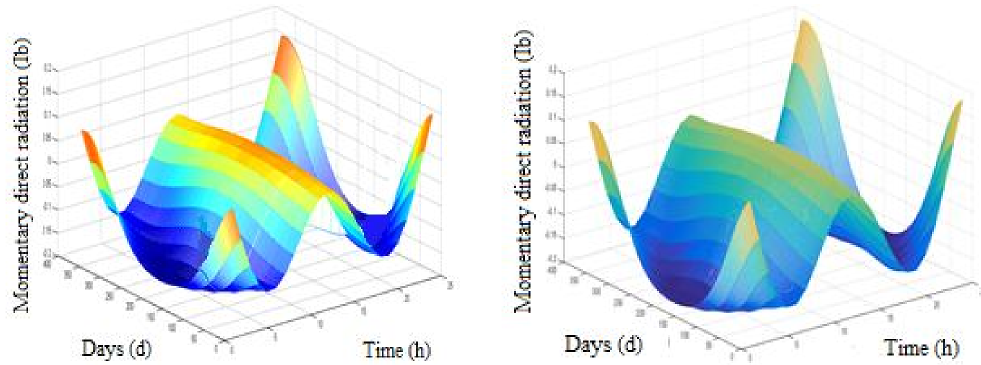
Attributes		Usak	Tokat	Attributes		Usak	Tokat
Total radiation	I_{max} W/m2	5.3881	4.7858	**Mom. dir. Rad.**	$I_{dbmax}(30°)$	0.8678	0.8933
	I_{min} W/m2	5.3500	4.7400		$I_{dbmin}(30°)$	-0.9670	-0.9721
Declination angle	d_{max}	23.6798	23.4488		I_{dbmax} (60°)	0.6190	0.7807
	d_{min}	-23.7398	-23.4468		I_{dbmin} (60°)	-0.7824	-0.8923
Sunrise hour angle	wmax	112.1015	112.9271		I_{dbmax} (90°)	0.0397	0.4992
	w_{min}	70.9865	69.8123		I_{dbmin} (90°)	-0.4182	-0.5882
Out-of-Atmosphere Radiation	$I_{o(max)}$ W/m2	281010	299215	**Mom. Dif. rad.**	$I_{bBmax}(30°)$	0.0395	0.1714
	$I_{o(min)}$ W/m2	-177450	-189100		$I_{bBmin}(30°)$	-0.1512	-0.1715
Transp. Index	B_{max}	0.3330	0.3567		$I_{bBmax}(60°)$	0.0489	0.1898
	B_{min}	-0.0011	-0.0111		$I_{bBmin}(60°)$	-0.1549	-0.1872
Total diffuse radiation	$Iy_{(max)}$ W/m2	6.2822	4.7881		$I_{bBmax}(90°)$	0.0458	0.1911
	$I_{y(min)}$ W/m2	5.1800	4.7400		$I_{bBmin}(90°)$	-0.1645	-0.1876
Function freq.	$A_{ts(max)}$	0.9500	0.8612				
	$A_{ts(min)}$	0.6418	0.5695	**Mom. reflecting rad.**	$I_{rBmax}(30°)$	0.0378	0.0486
Mom. Tot. Rad.	$I_{t(max)}$	1.7555	1.0011		$I_{rBmin}(30°)$	-0.0400	-0.0485
	$I_{t(min)}$	-0.9844	-1.1044		$I_{rBmax}(60°)$	0.1191	0.1499
Mom. Dif. Rad.	$(A_{ys})_{max}$	0.8991	0.8112		$I_{rBmin}(60°)$	-0.1521	-0.1673
	$(A_{ys})_{min}$	0.5799	0.5		$I_{rBmax}(90°)$	0.2781	0.3001
	$I_{d(max)}$	1.7853	0.9851		$I_{rBmin}(90°)$	-0.2921	-0.3258
Mom. direct rad.	$I_{d(min)}$	-0.5865	-0.9956				
	$I_{b(max)}$	0.0465	0.1854				
	$I_{b(min)}$	-0.1546	-0.1881				



(a)

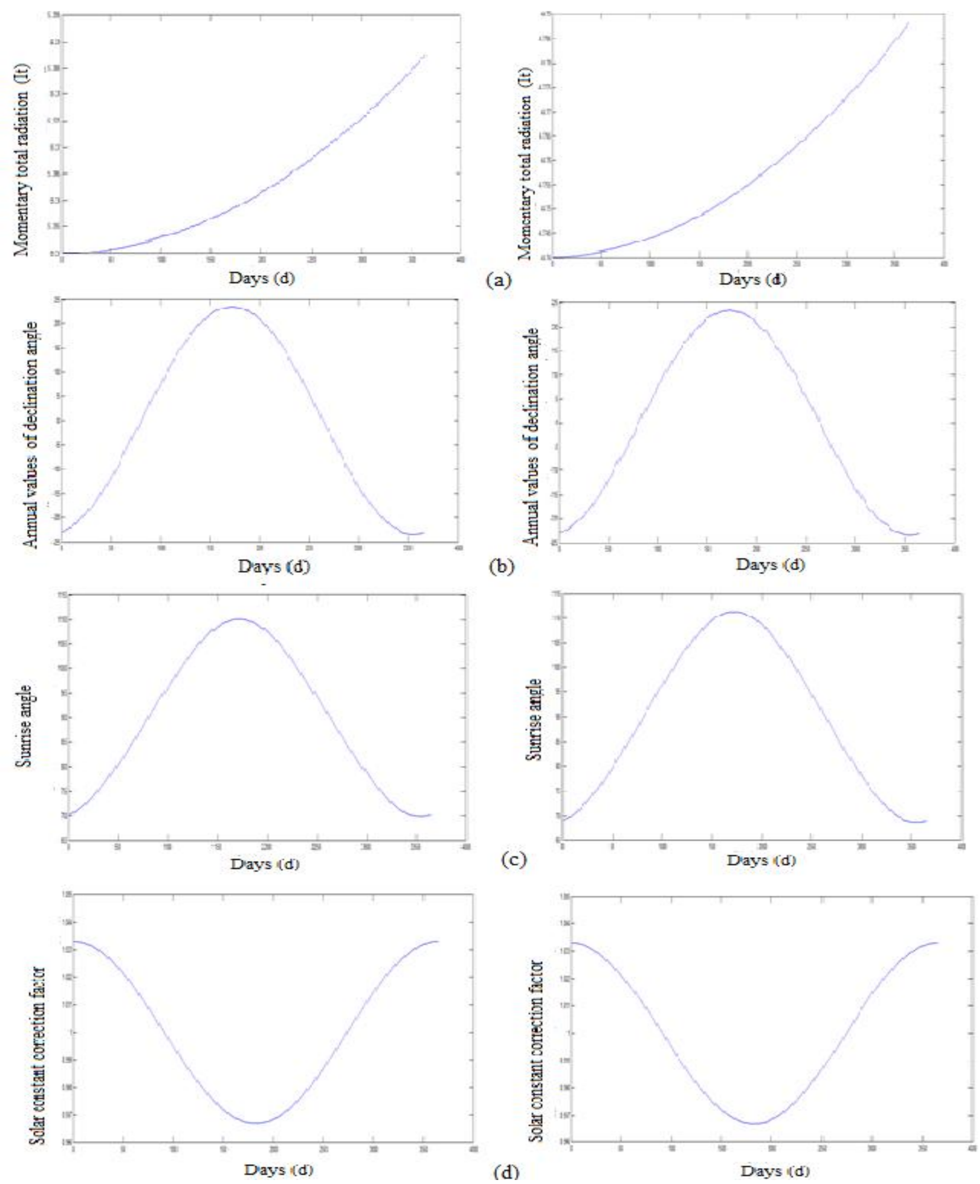


(b)



(c)

Fig. 6. Change of annual solar radiation values for 24-hour period on horizontal surfaces in Usak vs. Tokat



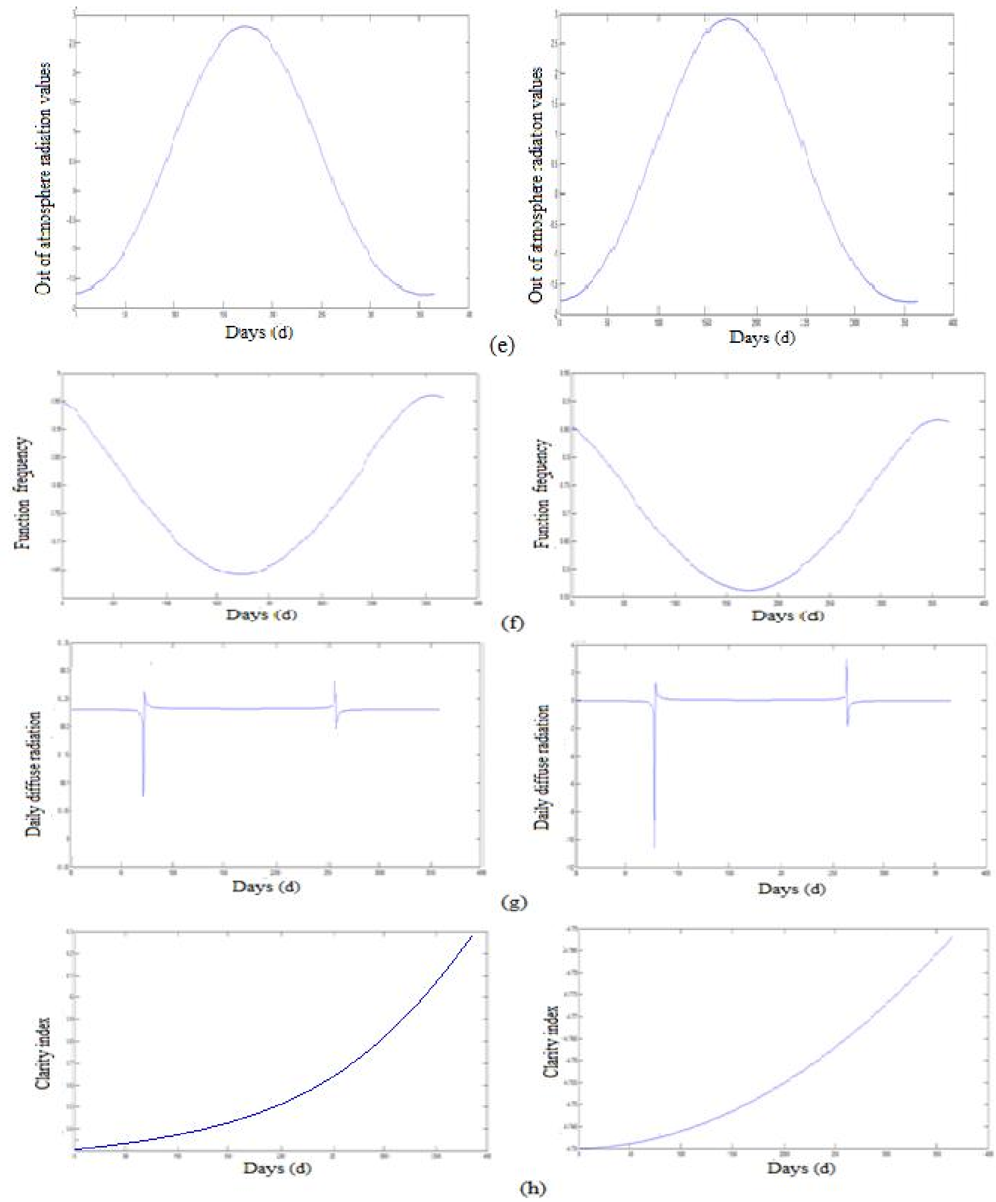
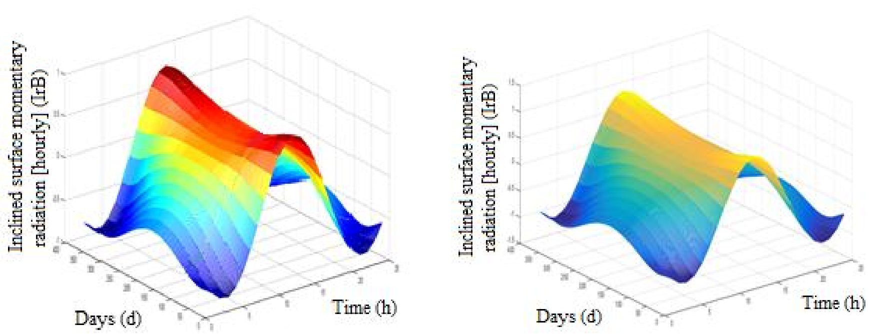
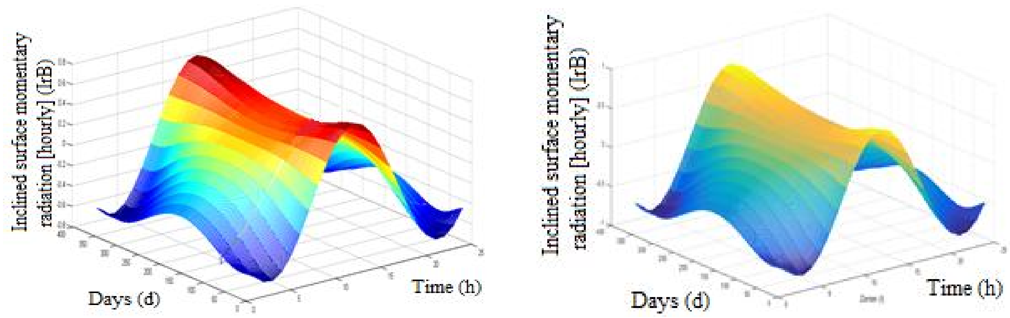


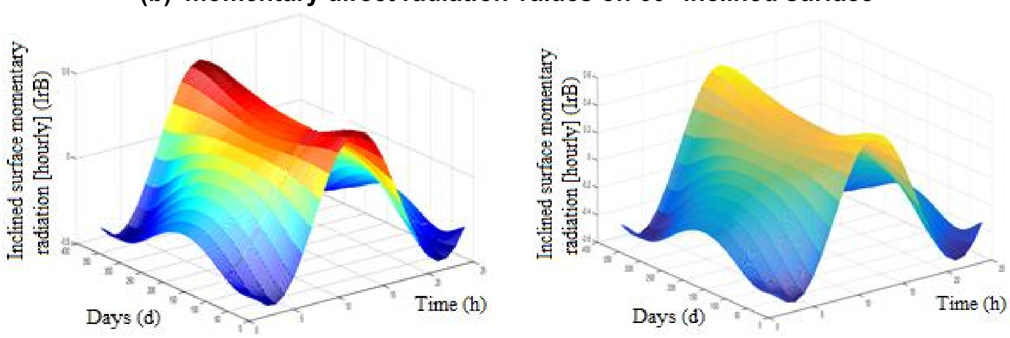
Fig. 7. Solar radiation on horizontal surfaces in Usak vs. Tokat



(a) momentary direct radiation values on 30° inclined surface

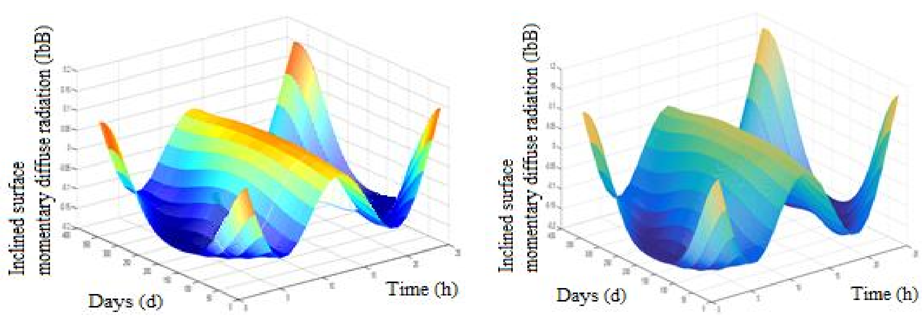


(b) momentary direct radiation values on 60° inclined surface

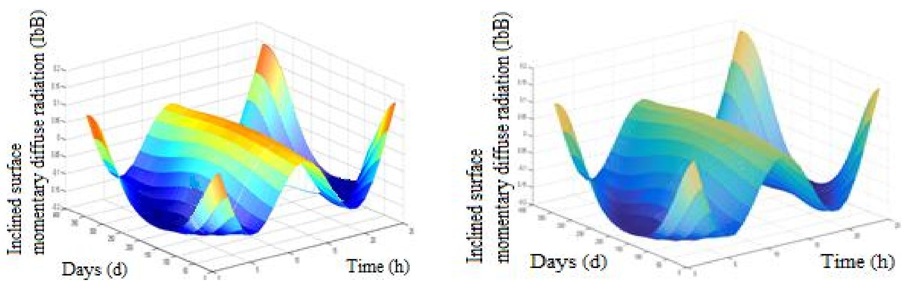


(c) momentary direct radiation values on 90° inclined surface

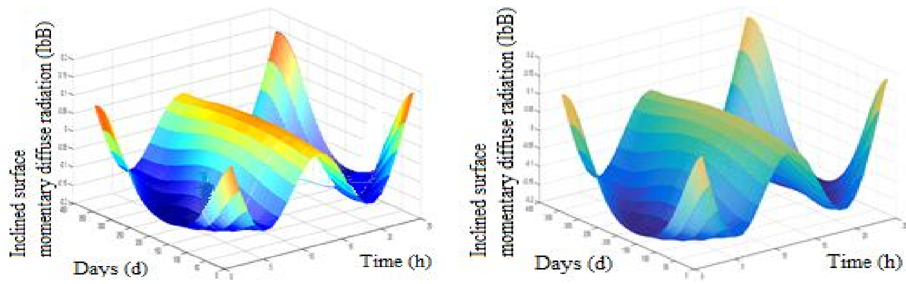
Fig. 8. Annual momentary direct radiation values on the inclined surface for 24-hour period



(a) 30° momentary diffuse radiation

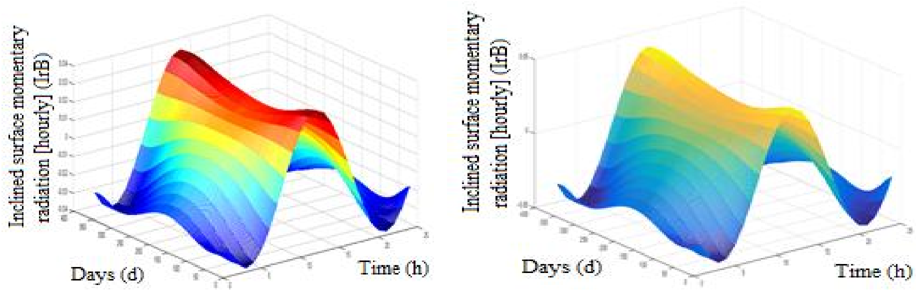


(b) 60° momentary diffuse radiation

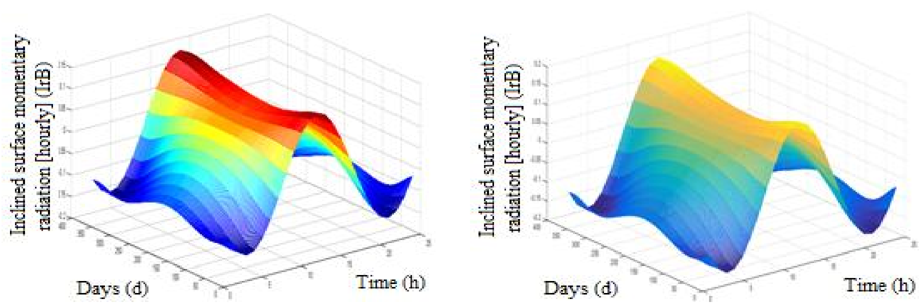


(c) 90° momentary diffuse radiation

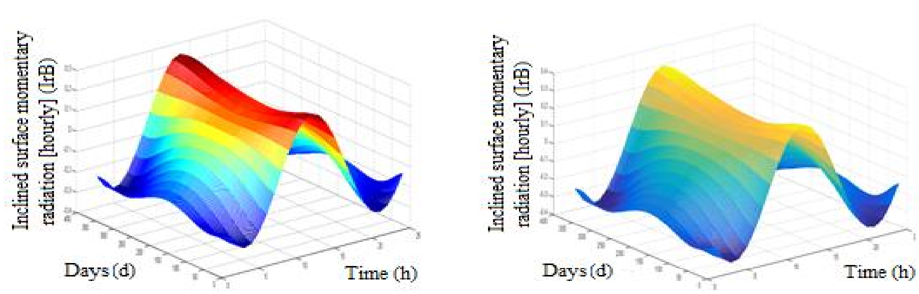
Fig. 9. Annual momentary diffuse radiation values for inclined surfaces



(a)30° total momentary radiation values



(b) 60° total momentary radiation values



(c) 90° total momentary radiation values

Fig. 10. Annual total momentary radiation values for inclined surface

5. CONCLUSION

Solar radiation values on inclined and horizontal surfaces are calculated through MATLAB software. Based on the calculations, the values of the indicators show that potential for photovoltaic systems in both cities corresponds to expected levels. An integral of planning the photovoltaic systems is comparing the predicted values with the actual ones. The performance of the system depends on various parameters. Using realistic values of radiation has great importance for designing the optimum system. This study aims to establish a reference for choosing the most efficient solar panel by relying on the real solar radiation values obtained for the most efficient photovoltaic system design. The solar radiation levels are evaluated to be at acceptable efficiency levels to design a photovoltaic system.

COMPETİNG İNTERESTS

Authors have declared that no competing interests exist.

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http://www.sciencedomain.org/review-history/27251