MEASUREMENT AND COMPARISON OF SOLAR RADIATION ESTIMATION MODELS FOR IZMIR/TURKEY: IZMIR INSTITUTE OF TECHNOLOGY CASE

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ABSTRACT

MEASUREMENT AND COMPARISON OF SOLAR RADIATION ESTIMATION MODELS FOR IZMIR/TURKEY: IZMIR INSTITUTE OF TECHNOLOGY CASE

Solar energy technologies offer a clean, renewable and domestic energy source, and are essential components of a sustainable energy in the future. Proper and adequate information on solar radiation and its components at a given location is very essential in the design of solar energy systems. Due to Turkey's location, solar energy potential is abundantly available. Consequently, it is worth to examine and conduct research on the solar energy source.

In this study, the global solar radiation data in Izmir were analyzed based on 3 years of global solar radiation data measured on a horizontal surface on the campus area of Izmir Institute of Technology. Actual data readings were made on a ten minute basis from January, 2005 to December, 2007. Monthly-average daily global radiation has been analyzed. A linear, a second-order and third order equations are designed for the calculation of the monthly-average daily global radiation in Izmir. The main objective is to estimate global solar radiation via models mentioned in the literature both for Turkey in general and for Izmir specifically; and to compare the results with the three new developed models. In addition to global solar radiation, diffuse solar radiation data were analyzed and proposed models for estimating the monthly average daily diffuse solar radiation, as well. Four new models were developed for diffuse solar radiation calculations and nine models from the literature have been used.

In order to confirm the results, four statistical methods have been used namely; mean bias error (MBE), root mean square (RMSE), t-statistic and relative percentage error. According to the statistical evaluation, it may be concluded that the new polynomial equation predict the monthly-average daily global solar radiance better than other available models.

ÖZET

İZMİR/TÜRKİYE İÇİN GÜNEŞ IŞINIM TAHMİN MODELLERİNİN ÖLÇÜM VE KARŞILAŞTIRMALARI: İZMİR YÜKSEK TEKNOLOJİ ENSTİTÜSÜ DURUM ÇALIŞMALARI

Güneş enerjisi yenilenebilir, temiz ve sürdürülebilir yerli enerji kaynağıdır. Bu nedenle gelecekteki en temel enerji elemanı olarak görülmektedir. Güneş enerjisine ait tasarım ve çalışmalarda, belirli bir bölge için güneş ışınımı ve bileşenlerine ait bilgiler önem taşımaktadır. Türkiye konumu nedeniyle yüksek bir güneş enerjisi potansiyeline sahiptir ve bu sebeple güneş enerjisi verilerini incelemek ve çalışmalar yapmak önem taşımaktadır.

Bu çalışmada İzmir Yüksek Teknoloji Enstitüsü'nde yatay bir alanda küresel güneş ışınım değerleri üç sene boyunca on 'ar dakikalık aralıklarla 2005 Ocak başından 2007 Aralık sonuna kadar ölçülmüştür. Bu veriler kullanılarak aylık ortalama günlük global ışınım belirlenmiştir. Literatürde Türkiye geneli ve sadece İzmir için daha önce çalışılmış 10 model kullanılarak aylık ortalama günlük global güneş ışınımı hesaplanmıştır. Ayrıca İzmir için lineer, ikinci ve üçüncü dereceden eşitlikler geliştirilmiştir. Bunun yanında, yaygın güneş ışınımı ile ilgili de benzer çalışmalar yapılmıştır. Literatürde yer alan Türkiye ve genel modellemelerden ve İzmir için ölçülmüş verilerden yola çıkılarak denklemler geliştirilmiş ve karşılaştırılmıştır. Eşitliklerin ve modellerin performans değerlendirmesi için ortalama hata (MBE), tahmini standart hataları (RMSE) ve t-istatistik yöntemleri kullanılmıştır. Yapılan karşılaştırmalar sonucunda 2. derece geliştirilen eşitliğin diğer modellere oranla daha başarılı sonuç verdiği görülmüştür.

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LIST OF SYMBOLS

G_{sc}	Solar constant (1367 W/m^2)
H	Monthly-average daily total radiation (W/m^2)
H_o	Monthly-average daily extraterrestrial radiation (W/m^2)
H_d	Monthly-average daily diffuse radiation (W/m^2)
k	Data number
n	Day of year starting from the 1^{st} of January
S	The monthly-average daily hours of bright sunshine (h)
S_o	The monthly-average of the maximum possible daily hours of bright sunshine (h)
Z	Altitude (m)
Φ	The latitude of the area (°)
δ	The solar declination (°)
w_0	Sunset hour angle (°)
k_t	Clearness index (H/H_o)
k_{dd}	Diffuse coefficient (H_d/H_o)
k_d	Cloudiness index (H_d/H)

LIST OF ABBREVIATIONS

DMI	Turkish State Meteorological Service
EIEI	Electrical Works Research Directorate
IYTE	Izmir Institute Of Technology
MBE	Mean Bias Error
RMSE	Root Mean Square Error
t-stat	t-statistic method
e	Relative Percentage Error
MPE	Mean Percentage Error
MAPE	Mean Absolute Percentage Error
SSRE	Sum of The Squares of Relative Errors
RSE	The Relative Standard Error
CAR	Central Anatolia Region
CBSR	Central Black Sea Region
IZTECH	Izmir Institute of Technology

CHAPTER 1

INTRODUCTION

Due to the developments in the technology, the energy need of people is increased. The sources of the energy are varied according to the technological progress. In the beginning, wood has been used to provide energy, and then coal is replaced instead of wood. Finding oil and natural gases, energy growth has been assured.

Energy demand is increasing by about 2% a year, and absorbs most of the requirements for energy development. New technology makes better use of already available energy through improved efficiency, such as more efficient fluorescent lamps, engines, and insulation. Using heat exchangers, it is possible to recover some of the energy in waste warm water and air, for example to preheat incoming fresh water. Hydrocarbon fuel production from pyrolysis could also be in this category, allowing recovery of some of the energy in hydrocarbon waste. Already existing power plants often can and usually are made more efficient with minor modifications due to new technology. New power plants may become more efficient with technology like cogeneration. New designs for buildings may incorporate techniques like passive solar. Light-emitting diodes are gradually replacing the remaining uses of light bulbs.

Renewable energy is considered to be the most important source to the world for the future. The decrease in the fossil fuels, made an orientation to the renewable energy sources such as sunlight, wind, rain, tides, and geothermal heat. Renewable energy is an alternative to fossil fuels and nuclear power, and was commonly called alternative energy in the 1970s and 1980s. In 2008, about 19% of global final energy consumption came from renewables, with 13% coming from traditional biomass, which is mainly used for heating, and 3.2% from hydroelectricity. New renewables (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.7% and are growing very rapidly. The share of renewables in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3% from new renewables.

While many renewable energy projects are large-scale, renewable technologies are also suited to rural and remote areas, where energy is often crucial in human development. Globally, an estimated 3 million households get power from small solar PV systems. Micro-hydro systems configured into village-scale or county-scale mini-grids serve many areas. More than 30 million rural households get lighting and cooking from biogas made in household-scale digesters. Biomass cook stoves are used by 160 million households.

Among the renewable energy resources solar energy is the most actual and usable in the world. It is the energy obtained from the heat and rays of the sun. The Sun is the star at the center of the Solar System. It is almost perfectly spherical and consists of hot plasma interwoven with magnetic fields. It has a diameter of about 1,392,000 km, about 109 times that of Earth, and its mass (about 2×10^{30}kilograms, 330,000 times that of Earth) accounts for about 99.86% of the total mass of the Solar System. Chemically, about three quarters of the Sun's mass consists of hydrogen, while the rest is mostly helium. Less than 2% consists of heavier elements, including oxygen, carbon, neon, iron, and others. The mean distance of the Sun from the Earth is approximately 149.6 million kilometers, though the distance varies as the Earth moves from perihelion in January to aphelion in July. At this average distance, light travels from the Sun to Earth in about 8 minutes and 19 seconds. The energy of this sunlight supports almost all life on Earth by photosynthesis, and drives Earth's climate and weather.

Solar energy can be used to generate electricity using photovoltaic solar cells and concentrated solar power. It can be used to heat buildings directly by passive solar building designs, or cooking and heating food with the help of solar ovens.

Solar technologies are broadly characterized as either passive solar or active solar depending on the way they capture, convert and distribute solar energy. Active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. Passive solar techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air.

The flexibility of solar energy is manifest in a wide variety of technologies from cars and calculators to huge photovoltaic plants. Recent price hikes and erratic availability of conventional fuels are factors that are renewing interest in solar heating technologies. Thus solar power is important to the very existence of the world as a whole.

To make use of solar energy in a better way, the feature of the sunlight and the amount of the solar power on a specific time and place are essential. Since the Sun is almost 150 million kilometers from the Earth, the energy density per unit time of the sunlight reaching the upper atmosphere of the Earth is only 1,367 W/m², which is known as solar constant. The solar constant is the amount of power that the Sun deposits per unit area that is directly exposed to sunlight.

At the core, solar energy is actually nuclear energy. In the inner 25% of the Sun, hydrogen is fusing into helium at a rate of about 7 x 10^{11}kg of hydrogen every second. Heat from the core is first primarily radiated, and then primarily convected, to the Sun's surface, where it maintains at a temperature of 5800 K.

The primary method of energy transport is electromagnetic radiation from the surface of the Sun; this form of heat transport depends greatly upon the surface temperature of an object for the amount and type of energy. Stefan-Boltzmann's Law tells us that the amount of energy that is radiated per unit area of surface depends upon the temperature of the object to the fourth power, i.e. energy/area is proportional toT^4. This means that the amount of energy that is emitted by the Sun, and therefore, the amount of solar energy that we receive here on Earth, is critically dependent upon this surface temperature. A change of 1% in the temperature of the Sun (58 K) can result in a change of 4% in the amount of energy per unit area that the world receives.

The type of radiation coming from the Sun also depends on temperature. The Sun is emitting electromagnetic radiation in wide variety of wavelengths. However, most of the radiation is being sent out in the visible spectrum due to its surface temperature. As an object gets hotter, the peak radiation will come from shorter wavelengths, and vice-versa.

The Sun radiates 1.6 x 10^7 watts of power per square meter from its surface at all wavelengths. However, by the time that it has reached the Earth's surface, this value is vastly reduced. Between the Sun's and the Earth's surfaces, the energy density of the radiation is lessened by spreading and absorption.

Many people think solar radiation comes in a direct beam from the sun. However, as radiation from the sun hits our atmosphere some is scattered in all directions. Some of this radiation is scattered towards the earth and is called diffuse solar radiation. The amount of solar radiation arriving at a particular point is called global solar radiation. In other words, in the earth's atmosphere, solar radiation is received directly (direct radiation) and by diffusion in air, dust, water, etc., contained in the atmosphere (diffuse radiation). As shown is Figure 1, global radiation is the sum of the reflected radiation, direct irradiation and the diffuse solar radiation on any plane. Values of global and diffuse radiations for individual hours are essential for research and engineering applications.

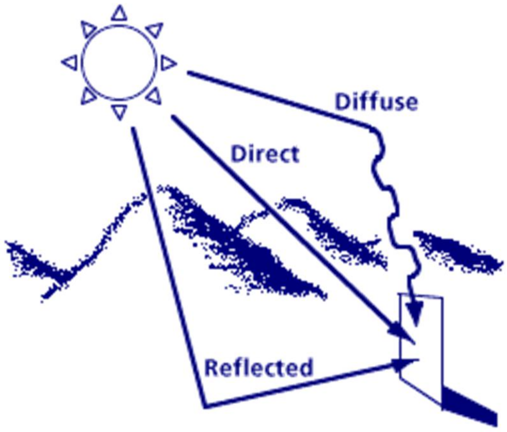


Figure 1. Direct, diffuse and reflected solar radiation
(Source: inforse; June, 2010)

The general equation for the ratio of the monthly-average daily radiation on a horizontal surface (H) to the monthly-average daily extraterrestrial radiation (H_o) depending on sunshine duration computed from the following equation:

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) \qquad (1.1)$$

The "a" and "b" values are known as Angstrom constants and they are empirical. S is the monthly-average daily hours of bright sunshine and S_o is the monthly-average of the maximum possible daily hours of bright sunshine.

Monthly mean daily maximum possible sunshine duration is calculated in hours as (Duffie and Beckman, 1991)

$$S_0 = \frac{2w_0}{15} \qquad (1.2)$$

Solar radiation incident outside the earth's atmosphere is called extraterrestrial radiation. The monthly-average daily extraterrestrial radiation on a horizontal surface calculated from

$$H_o = \frac{24}{\pi} G_o \left(\cos\phi \cos\delta \sin w_0 + \frac{\pi}{180} w_0 \sin\phi \sin\delta\right) \quad (1.3)$$

where,

$$G_o = G_{sc} \left(1 + 0{,}033 \cos\left(\frac{360n}{365}\right)\right) \quad (1.4)$$

and

$$\delta = 23.45 \sin\left[\frac{360(284+n)}{365}\right] \quad (1.5)$$

G_{sc} is the solar constant (=1,367 W/m²), ϕ is the latitude of the area, δ is the solar declination that is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis, n is the number of the day starting from the 1st of January and w_0 is sunset hour angle, which can be calculated from the equation as follows:

$$\cos w_0 = -tan\phi \, tan\delta \quad (1.6)$$

Diffuse radiation is the second type of solar radiation. The solar radiation received from the sun after its direction has been changed by scattering in the atmosphere. The total radiation on a horizontal surface is recorded at a large number of locations, while diffuse radiation, needed in many solar energy applications, is measured in comparatively few locations. The diffuse fraction under clear-sky conditions may be calculated theoretically. However, it is common practice for the large number data to be condensed and presented in simple useable form obtained from the measurements for various types of users. Correlation used for predicting monthly average daily values of diffuse radiation may be classified in four groups as: (i) from the clearness index (k_t= H/ H_o), (ii) from the relative sunshine duration or sunshine fraction (S/ S_0), (iii) from the diffuse coefficient (k_{dd} = H_d/ H_o), and (iv) from the diffuse fraction or cloudiness index (k_d= H_d/H).

Solar energy is considered as a key source not only for the world but also for Turkey. Turkey lies in a sunny belt between 36° and 42° N latitudes and is geographically well situated with respect to solar energy potential. Turkey is located in an advantageous position in Europe for the purposes of solar power. The global solar radiation values on a horizontal surface and daily sunshine hours are measured in Turkey by many recording stations in Turkish State Meteorological Service (DMI).

According to these data, Turkey's average annual total sunshine duration is calculated as 2,640 hours (daily total is 7.2 hours), and average total radiation pressure as 1,311 kWh/m²-year (daily total is 3.6 kWh/m²). Solar energy potential is calculated as 380billion kWh/year. In Table 1, it can be seen that Turkey's monthly-average solar radiation values and sunshine duration.

Table 1. Turkey's monthly-average solar radiation data
(Source: EIE; June,2011)

Months	**Monthly-average solar radiation** **(Kcal/cm2-month)**	**(kWh/m2-month)**	**Sunshine dur. (h/month)**
January	4.45	51.75	103.0
February	5.44	63.27	115.0
March	8.31	96.65	165.0
April	10.51	122.23	197.0
May	13.23	153.86	273.0
June	14.51	168.75	325.0
July	15.08	175.38	365.0
August	13.62	158.40	343.0
September	10.60	123.28	280.0
October	7.73	89.90	214.0
November	5.23	60.82	157.0
December	4.03	46.87	103.0
Total	112.74	1,311	2,640
Average	308.0 kcal/cm2-day	3.6 kWh/m2-day	7.2 h/day

The main objectives of the present study are:

- To establish monthly-average daily global and diffuse radiation values for Izmir, Turkey.
- To develop new models via to the equations in the literature for Izmir.
- To compare all the models by using statistical methods.

This thesis is composed of 7 chapters. In order; Chapter 1 is the introduction part. Chapter 2 gives a brief explanation of literature survey. Chapter 3 is concerned with the solar radiation measurements. First part is prepared for the experimental data. Such components as pyranometer, data logger specifications are expressed one by one. Last part is for statistical methods. Chapter 4 consists of the analysis of global solar radiation and its models. New developed models are also mentioned in this chapter.

Chapter 5 is concerned with the analysis of diffuse solar radiation. In this chapter, the study is divided into 4 groups. Each group has got three models which one of them is the new calculated model. Chapter 6 is concerned with the calculation results of solar energy on the horizontal surface both global and diffuse radiations. Finally, in Chapter 7, conclusions are presented.

CHAPTER 2

LITERATURE SURVEY

2.1. Global Solar Radiation

The estimation of daily global solar radiation has been reviewed in most of the researches based on the duration of sunshine, identifying the best model and determining different coefficients for several locations.

Diez-Mediavilla, et al. (2004) made an analysis of 10 arithmetic models used to calculate diffuse solar irradiance on inclined surfaces in Valladolid, Spain. The actual data readings were taken hourly and daily basis from the 1^{st} of August, 1998 until the 15^{th} of March, 2000. Three statistical methods have been used to confirm the results. Taking the area’s feature into account was mentioned important for diffuse irradiance on inclined surfaces. In conclusion the Muneer model and the the Reindl model gives the best results for hourly and for daily values.

Stone (1993) proposed t- statistics as a statistical indicator for the evaluation and comparison of solar radiation estimation models. A relationship was developed for the t-statistic by using data published in the solar energy literature as a function of the widely used root mean square and mean bias errors. It was shown that the use of the root mean square and mean bias errors separately can lead to the incorrect selection. As a result, the t-statistic method can be used in conjunction with the root mean square and mean bias errors to more reliably assess a model's analysis.

Akpabio et al. (2004) presented a quadratic form of the Angstrom-Prescott model to estimate global solar radiation at Onne (lat. 4°46′N, long. 7°10′E), a tropical location. Ogelman et al. model, Akinoglu and Ecevit model, Fagbenle's model were compared with the ones developed for the Nigerian environment. The results showed that the relationship between clearness index and relative shine in quadratic form is to some extent locality-dependent.

The measured data of global and diffuse solar radiation on a horizontal surface, the number of bright sunshine hours, mean daily ambient temperature, maximum and minimum ambient temperatures, relative humidity and amount of cloud cover for

Jeddah (lat. 21°42′37″N, long. 39°11′12″E), Saudi Arabia, during the period (1996–2007) were analyzed by El-Sebaii et al. (2009). The monthly averages of daily values for the meteorological variables calculated. The data were then divided into two sets. The sub-data set 1 (1996–2004) was employed to develop empirical correlations between the monthly average of daily global solar radiation fraction (H/H_o) and the various weather parameters. The sub-data set 2 (2005–2007) were then used to evaluate the derived correlations. The total solar radiation on horizontal surfaces was separated into the beam and diffuses components. Empirical correlations for estimating the diffuse solar radiation incident on horizontal surfaces have been proposed. The total solar radiation incident on a tilted surface with different tilt angles was then calculated using both Liu and Jordan isotropic model and Klucher's anisotropic model. It was inferred that the isotropic model is able to estimate the total solar radiation incident on a tilted surface more accurate than the anisotropic one. At the optimum tilt angle, the maximum value was obtained as ~36 (MJ/m^2day) during January.

A quadratic relationship between solar insolation and duration of solar radiation data has been investigated by Aksoy (1996) in order to estimate monthly average global irradiance for Ankara, Antalya, Samsun, Konya, Urfa and Izmir. A general quadratic formula was found that represents the whole of Turkey. A quadratic model was chosen because it better represents population distribution than the linear Angstrom model, especially at extreme points. He concluded that monthly global solar irradiance can be estimated with about 4% relative error with the quadratic formula.

Ulgen and Hepbasli (2008) used solar radiation data for Ankara (lat. 39°57'N, long. 32°53'E, alt. 894 m), Istanbul (lat. 40°58'N, long. 29°05'E, alt. 39 m) and Izmir (lat. 38°24'N, long. 27°10'E, alt. 15 m) of Turkey to establish a relationship between the monthly average daily diffuse fraction and the monthly average daily diffuse coefficient with the monthly average daily clearness index and monthly-average daily sunshine fraction. 32 different models and 8 new models were compared due to the widely used 8 statistical indicators. They concluded that the new models predict the values of cloudiness index and the diffuse coefficient as a function of clearness index and sunshine fraction for the three cities better than other available models.

Gunes (2001) examined the variation of monthly-average daily global solar radiation in 11 stations located in 9 cities in Turkey. Five of the stations were depending on Turkish State Meteorological Service (DMI), and the others were belonging to

Electrical Works Research Directorate (EIEI). Kilic and Ozturk's model (1983), Ogelman et al.'s model (1984) and Aksoy's model (1997) were compared according to the values of mean quadratic error, mean absolute error and correlation coefficient. It has been seen that the most successful model was Ogelman et al.'s model.

Kaygusuz and Ayhan (1997) made analysis of measured solar data in the form of hourly-average solar irradiation, monthly-average daily global solar radiation and percentage frequency distribution in Trabzon, Turkey (lat. 41°10'N, long. 40°20'E). The calculations were based on generally accepted equations. Due to the calculations the hourly-average global solar radiation and hourly-average diffuse solar radiation were plotted. They concluded that the maximum value of the monthly-average daily global radiation was recorded in June with an amount of 21.6 MJ/m^2. The monthly-average daily clearness index varied between 0.29 in March and 0.47 in June. The highest values of hourly radiation were recorded between 11am-12am during the day.

Bakirci (2006) presented a third-order equation for the calculation of the monthly-average daily global solar radiation for Erzurum, Turkey (lat. 39°55'N, long. 41°16'E, alt. 1869 m). Measured data taken from Turkish State Meteorological Service for four years. Additionally for computing the monthly-average daily global solar radiation 9 models available in the literature were used. The models were examined by three statistical methods respectively, mean bias error (MBE), root mean square error (RMSE), and t-statistic. It has been concluded that the lowest RMSE and MBE values were gathered from the third-order equation model and the lowest t-statistic value is taken from the model of Ulgen and Hepbasli. Except Tiris' model, all used models were appropriate for calculating the monthly-average daily global radiation in Erzurum due to t-critic value that is 3.106.

Ogulata and Ogulata (2001) calculated the monthly-average daily and hourly global, diffuse and direct radiations on a horizontal surface in Adana, Turkey (lat. ~37°00'N, long. ~35°20'E, alt. ~20 m). They concluded that the maximum monthly-average daily global radiation was recorded as 18.51 MJ/m^{2}day in July. Diffuse radiation values range from 9.1 MJ/m^{2}day in July to 2.8 MJ/m^{2}day in January. The equations used in the study were applicable for Adana for predicting global and hourly solar radiations.

Celik (2005) analyzed the solar radiation data in Ankara,Turkey (lat. 39°95'N, long. 32°88'E, alt. 891 m) based on 6 years of global solar radiation data measured on a horizontal surface by the DMI. The yearly and monthly optimum tilt angles were determined by converting available data. It has been concluded that the yearly total optimal tilt angle was 39.40° for the year 2000. The smallest optimal tilt angle was 6.7° in June and the largest was 65.2° in November.

Ulgen and Hepbasli (2004) reviewed solar radiation models for Turkey in general and some of its provinces. 41 models used to estimate the monthly average daily global solar radiation on a horizontal surface were categorized in four groups namely; lineer models, polynomial or quadratic models, angular models, and modified Angstrom-type models. They concluded that most of solar radiation models developed for Turkey over a 19 year period was in the polynomial forms and the models gave reasonably well results for Turkey or elsewhere with similar climatic conditions.

Aras et al. (2006) developed empirical models to predict the monthly-average daily global solar radiation over twelve provinces in the Central Anatolia Region (CAR) of Turkey and to compare calculated values obtained from developed models with data measured by the Turkish State Meteorological Service (DMI) in the period from January 1990 to December 1996 based on the various statistical methods. The general linear, quadratic, and cubic polynomial models were derived for the region. Values for the maximum monthly average daily measured global solar radiation ranged from 24 (for Cankiri, Turkey) and 27.10 (for Nevsehir, Turkey) to 25.85 MJ/m2. Maximum average daily measured sunshine duration values were in the range of 9.6 (for Cankiri, Turkey) and 11.90 (for Nevsehir and Sivas, Turkey) to 11.12 h.

Ulgen and Hepbasli (2004) compared some existing models used for estimating the monthly-average daily global solar radiation for Istanbul, Ankara and Izmir of Turkey. They also developed some empirical models for these cities. The MBE, RSME, MPE, and t-statistic methods were used to evaluate the performance of the models. They concluded that the 2 new empirical models were found to be reasonably good for all the test methods.

A new correlation for the estimation of monthly average daily global solar radiation was developed by Akinoglu and Ecevit (1990) and they compared with the correlations of Rietveld, Benson et al., Ogelman et al. The overall results show that the quadratic form gives better performance in terms of global applicability. The new quadratic model should be preferred for the monthly average global solar radiation estimation when the data for bright sunshine hours are available.

Togrul et al. (2002) developed some statistical relations in order to estimate monthly mean daily global solar radiation in Turkey. The global solar radiation was measured by Kipp pyranometer in 6 observation stations. Various regression analyses were applied to estimate monthly mean solar radiation in Turkey, by using the daily fraction of possible hours, (n/N), where n is the measured sunshine duration in a day and N is the theoretical day length of that day. Three statistical tests, root mean square error (RMSE) and mean bias error (MBE), and t-statistic were used to evaluate the accuracy of the correlations. It was seen that the equations which include the summer and winter periods gave better results than the others in all of the developed equations.

2.2. Diffuse Solar Radiation

Ulgen and Hepbasli (2001) showed the monthly-average global and diffuse solar radiation data. The theoretical analysis of the monthly-average clearness index was defined. As a result, the value of the monthly-average global radiation varied from 5964 kJ/m^2 in December to 27.154kJ/m^2 in June. The values of the monthly-average daily clearness index raged from 0.45 to 0.66. The developed models were found to be suitable and reliable.

Ulgen and Hepbasli (2002) used hourly global and diffuse radiation measurements over a 5 year period to establish a relationship between the daily diffuse fraction and the daily clearness index for Izmir, Turkey. The comparisons of the results were done with other correlations available in the literature. After generating the results from 16 models, the best results were obtained from the higher order polynomial models.

Aras et al. (2005) developed 12 new models for estimating monthly average daily diffuse solar radiation on a horizontal surface in the CAR and the diffuse solar radiation models in the literature were analyzed in detail. In conclusion, the provinces in the CAR have almost the same diffuse solar radiation values.

Tarhan and Sari (2004) analyzed global and diffuse solar radiation in 5 cities in the CBSR. A quadratic polynomial equation was empirically developed to predict the monthly average daily global radiation. A hybrid model was also developed based on the predictions of six existing models. As a result, the quadratic model has been chosen as the best model for the solar radiation data of the CBSR region.

Jiang (2008) used nine diffuse radiation models for the daily data between January 1, 1994 and December 31, 1998 from 16 stations all over China. Validation of 9 models for predicting monthly mean daily diffuse solar radiation has been performed by using the statistical errors MPE, MBE and RMSE. It was found that the second degree polynomial relationship, Iqbal model, is suitable for diffuse radiation estimation in China. The Iqbal model works better in the eastern part of China than in the west. The A.A. El-Sebaii model could not be used to estimate diffused radiation accurately in China. The Liu and Jordan model could also be used for diffuse radiation estimation in China.

An analysis of measurement for Gebze, Turkey has been done by Tiris et al. Applying measured data correlation models for calculating the hourly and monthly diffuse radiations were derived for nine years. As a result, the maximum value of the monthly-average daily global radiation was 24 MJ/m^2 in June. And the minimum value was 2.2 MJ/m^2 recorded in December.

Ahmad and Tiwari (2009) reviewed solar radiation models for predicting the average daily and hourly global radiation, beam radiation and diffuse radiation on horizontal surface. It was observed that Collares-Pereira and Rabl model as modified by Gueymard (CPRG) yielded the best performance for estimating mean hourly global radiation incident on a horizontal surface in India. Estimations of monthly average hourly beam and diffuse radiation are discussed. It was observed that Singh-Tiwari and Jamil-Tiwari models generally give better results for climatic conditions of India. Fifty models using the Angstrom–Prescott equation to predict the average daily global radiation with hours of sunshine are considered. It was reported that Ertekin and Yaldiz model showed the best performance against measured data of Konya, Turkey.

Ulgen and Hepbasli (2008) developed 8 new models for estimating the monthly average daily diffuse solar radiation on a horizontal surface in three big cites of Turkey. The new models are then compared with the 32 models available in the literature in terms of the widely used statistical indicators. It may be concluded that the new models predict the values of cloudiness index and diffuse coefficient as a function of clearness index and sunshine fraction for three big cities in Turkey better than other available models.

Che et al. (2010) used forty years of daily global and diffuse radiation data to characterize the atmospheric conditions at 14 stations in China. These sites are located so widely throughout China that they can be considered representative of different climatic regions of China. Two polynomial models have been developed to simulate clearness index and diffuse ratio at each station and also they proposed a trigonometric model in conjunction with a sine and cosine wave for estimating daily global solar radiation. The statistical estimator of root mean square (RMSE) showed that the developed models are suitable for simulations of clearness index and diffuse ratio at most premium solar radiation stations in China.

CHAPTER 3

EXPERIMENTAL SOLAR RADIATION DATA AND STATISTICAL METHODS

3.1. Experimental Data

The experimental set-up is located at the Mechanical Engineering Department in Izmir Institute of Technology. Its latitude and longitude are 38°42'N, 27°12'E, respectively.

Pyranometers are used for measuring global radiation data. Through these instruments most of the available data on solar radiation are obtained. A pyranometer produces voltages from the thermopile detectors that are a function of the incident radiation. It is necessary to use a potentiometer to detect and record this output. Radiation data usually must be integrated over some period of time, such as an hour or a day.

Two additional kinds of measurements are made with pyranometers; measurements of diffuse radiation on horizontal surfaces and measurements of solar radiation on inclined surfaces.

In this study, the global radiation on a horizontal surface was measured at an interval of 10 minute by using a Kipp-Zonen pyranometer (Model CM11) during the experiments. The CM11 (Figure 2) pyranometer is intended for high accuracy global solar radiation measurement research on a plane/level surface.

The CM11 houses a second built-in complimentary sensing element (temperature compensation element), in addition to the black receiving detector. Calibrated to identical sensitivity as the receiving detector, the compensation element is connected in anti-series to the receiving detector. Instrument output signal is measured across the entire anti-series circuit. Any change in body temperature, due to thermal shock or temperature gradient effect, is quickly detected by the built-in compensation element, and an offset correction signal is applied to the instrument output signal.

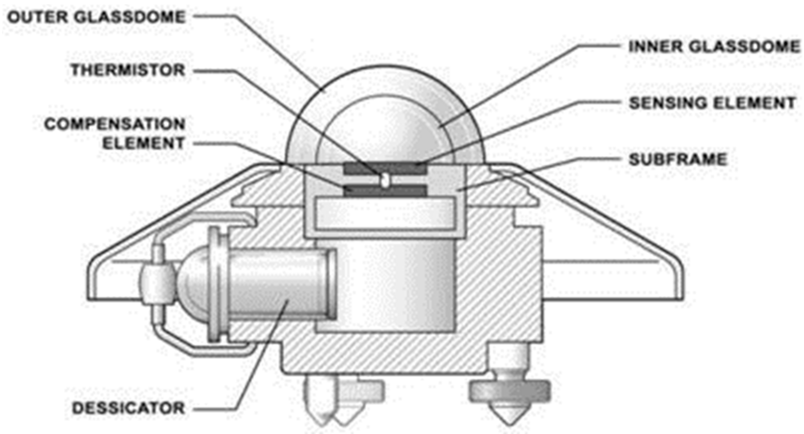


Figure 2. Approximate construction of CM11
(Source: Kipp-Zonen, 2010)

Table 2. CM11 specfications
(Source: Kipp-Zonen, 2010)

Spectral range	305-2800 nm
Sensitivity	5.14 uV/W/m2
Internal resistance	700-1500 Ohms
Response time	15 s
Nonlinearity	<+0.6% (<1000W/m2)
Zero offset	+7 W/m2
ISO-9060 Class	Secondary Standard

Measurements of diffuse radiation can be made with pyranometers by shading the instrument from beam radiation. This is usually done by means of shadow ring, as shown in Figure 3. The ring is used to allow continuous recording of diffuse radiation without the necessity of continuous positioning of smaller shading devices; adjustments need to be made for changing declination only.

The data logger (Figure 4) is a 10 channel data logger that functions both as a data logging device and a multichannel, auto ranging meter. The LI-1000 data logger is also well suited to measure low impedance voltage sensors such as thermocouples, and sensors with a pulsed output .A wide variety of other sensors for environmental and industrial test and measurement can also be measured with the LI-1000 data logger. In this study, a 10 channel LI-1000 Data Logger is used and two current input channels are located on the two sealed BNC connectors so the equipment above is not used. Data is output through an RS-232C interface cable, maximum, minimum reading.

Figure 3. Shadow Ring for CM11 Pyranometer

Figure 4. Data logger

The site is located a way from a shadow will not be cast on it anytime and the site is chosen away from any obstruction over the azimuth range between earliest sunrise and latest sunset should have an elevation not exceeding 5° . This is important for an accurate measurement of the direct solar radiation. The diffuse solar radiation is less influenced by obstructions near the horizon. The pyranometer is located far from light-colored walls or other objects likely to reflect sunlight onto it.

Meteorological data including temperature, relative humidity, global solar radiation, and precipitation etc. for Izmir Institute of Technology (IZTECH) have been recorded since 2005. Solar radiation data were compiled from IZTECH Meteorological Station in Figure-3 from February, 2005 to May, 2007. It was over a period of 821 days, and 116,101 for 10-minute values. On the other hand, the diffuse solar radiation data that is used in the study have been recorded from February, 2004 to December, 2005.

3.2. Statistical Methods

In the literature, there are several statistical test methods used to statistically evaluate the performance of the models of solar radiation estimations. Among these, correlation mean bias error (MBE), root mean square error (RMSE), and the t-statistic (t-stat) errors are the most widely used ones.

3.2.1. Mean Bias Error

The mean bias error (MBE) provides information on the long-term performance of the correlations by allowing a comparison of the actual deviation between calculated and measured values term by term. The ideal value of the MBE is zero. The MBE is given by,

$$\mathrm{MBE} = \sum_{k=0}^{n} y_k - x_k \tag{3.1}$$

where, y_k is the kth calculated value, x_k is the kth measured value, and n is the total number of observations.

3.2.2. Root Mean Square Error

The root-mean-square error (RMSE) is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed from the thing being modeled or estimated. RMSE is a good measure of precision. The value of RMSE is always positive, representing zero in the ideal case. The RMSE may be computed from the following equation

$$\mathrm{RMSE} = \sqrt{\sum_{k=0}^{n} (y_k - x_k)^2 / n} \tag{3.2}$$

3.2.3. t-Statistic Method

After an estimation of a coefficient, the t-statistic for that coefficient is the ratio of the coefficient to its standard error.

In the literature, Stone (1993) demonstrated that MBE and RMSE separately do not represent a reliable assessment of the model's performance and can lead to the false selection of the best model from a set of candidates. To determine whether or not the equation estimates are statistically significant, Stone (1993) proposed t-stat as:

$$\mathrm{t-stat} = \sqrt{\frac{(n-1)\mathrm{MBE}^2}{\mathrm{RMSE}^2 - \mathrm{MBE}^2}} \tag{3.3}$$

3.2.4. Relative Percentage Error (e)

The relative percentage error is given by;

$$e = \left(\frac{y_k - x_k}{x_k}\right) 100 \tag{3.4}$$

where; y_k is the kth calculated value, x_k is the kth measured value. The "e" value provides the percentage deviation between the calculated and measured data. The ideal value of "e" is zero.

CHAPTER 4

ANALYSIS OF GLOBAL RADIATION MODELS

In the literature, many models were developed to estimate the global solar radiation. In this study 9 models and 3 new developed equations were used to estimate monthly-average global solar radiation. They were grouped and examined according to type of the equation that were namely, angular equations (Group 1), linear equations (Group 2), quadratic equations of second (Group 3) and third order (Group 4).

4.1. Kılıc and Ozturk's Model

The coefficients a and b were determined as a function of solar declination (δ) , latitude of sight (ϕ) and altitude (Z).

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) \quad (4.1)$$

where,

$$a = 0.103 + 0.000017Z + 0.198\cos(\phi - \delta) \quad (4.2)$$

$$b = 0.533 + 0.165\cos(\phi - \delta) \quad (4.3)$$

The model was in the angular type group (Group1) of which were derived by modifying the original Angstrom-type equation.

4.2. Akinoglu and Ecevit's Model

The following equation placed in Group 3 was obtained for the various regions of Turkey.

$$H = H_o\,[0.145 + 0.845\left(\frac{S}{S_o}\right) - 0.280\left(\frac{S}{S_o}\right)^2] \quad (4.4)$$

4.3. Tasdemiroglu and Sever's Model

A second order polynomial equation for Turkey's general was formulated as:

$$H = H_o\,[0.195 + 0.676\left(\frac{S}{S_o}\right) - 0.142\left(\frac{S}{S_o}\right)^2] \tag{4.5}$$

4.4. Oz's Model (1997)

For the whole of Turkey, Oz obtained a general equation from Group 3 by using data measured at 9 stations. It was as follows:

$$H = H_o\,[0.3420 + 0.5002\left(\frac{S}{S_o}\right) - 0.1014\left(\frac{S}{S_o}\right)^2] \tag{4.6}$$

4.5. Aksoy's Model

Aksoy developed a second order quadratic equation (Group 3) in order to calculate monthly-average global irradiance for 6 places in Turkey, as follows:

$$H = H_o\,[0.148 + 0.668\left(\frac{S}{S_o}\right) - 0.079\left(\frac{S}{S_o}\right)^2] \tag{4.7}$$

4.6. Ulgen and Ozbalta's Model

The following equation is belonged to Group 3 and it is estimated for Izmir, Turkey.

$$H = H_o\,[0.0959 + 0.9958\left(\frac{S}{S_o}\right) - 0.3922\left(\frac{S}{S_o}\right)^2] \tag{4.8}$$

4.7. Togrul and Togrul's Model

Togrul et al. obtained below mentioned equation for Ankara, Antalya, Izmir, Aydin, Adana and Elazig to estimate monthly-average global solar radiation.

The equation was in the Group 2.

$$\frac{H}{H_o} = 0.318 + 0.449 \left(\frac{S}{S_o}\right) \tag{4.9}$$

4.8. Ulgen and Hepbasli's Model

Based on measurements made in the Meteorological Station of Solar Institute, Ege University, Izmir from 1994 to 1998, a third order quadratic equation (Group 4) is developed. The formula is given by,

$$H = H_o \left[0.2408 + 0.3625 \left(\frac{S}{S_o}\right) + 0.4597 \left(\frac{S}{S_o}\right)^2 - 0.3708\left(\frac{S}{S_o}\right)^3 \right] \tag{4.10}$$

4.9. Ulgen and Hepbasli's Model

Using the data available for Ankara, Istanbul and Izmir over a 19-yr period, Ulgen and Hepbasli developed the following equation:

$$H = H_o \left[0.2854 + 0.2591 \left(\frac{S}{S_o}\right) + 0.6171 \left(\frac{S}{S_o}\right)^2 - 0.4837\left(\frac{S}{S_o}\right)^3 \right] \tag{4.11}$$

4.10. New Developed Equation 1

A linear equation has been developed to estimate monthly-average daily global solar radiation in Izmir, as follows:

$$H = H_o\left[0.263 + 0.512 \left(\frac{S}{S_o}\right)\right] \tag{4.12}$$

4.11. New Developed Equation 2

Using regional data, a Group-3 type of equation has been developed that was given by;

$$H = H_o \left[0.238 + 0.610\left(\frac{S}{S_o}\right) - 0.085 \left(\frac{S}{S_o}\right)^2 \right] \tag{4.13}$$

4.12. New Developed Equation 3

Third order quadratic correlation of Group-4 has been obtained for monthly-average daily global solar radiation. It was as follows:

$$H = H_o\,[0.371 + 0.297\left(\frac{S}{S_o}\right) - 0.575\left(\frac{S}{S_o}\right)^2 + 0.932\left(\frac{S}{S_o}\right)^3] \qquad (4.14)$$

CHAPTER 5

ANALYSIS OF DIFFUSE RADIATION MODELS

Hourly global radiation on horizontal surfaces is available for many stations, but relatively few stations measure the hourly diffuse radiation.

In this section, 8 models have been reviewed and 4 new models were estimated to establish the monthly- average diffuse radiation. They were grouped and examined not like in the past chapter, but according to type of the equation expressed the monthly average daily diffuse solar radiation as a function of measured sunshine duration, measured global solar radiation and extraterrestrial solar radiation.

5.1. H_d as a Function of H and the Clearness Index (Group 1)

5.1.1. Tasdemiroglu and Sever's Model

The model was prepared for Turkey in general. The equation is:

$$H_d = H\left[1.6932 - 8.2262\left(\frac{H}{H_o}\right) + 25.5532\left(\frac{H}{H_o}\right)^2 - 37.807\left(\frac{H}{H_o}\right)^3 + 19.8178\left(\frac{H}{H_o}\right)^4\right] \quad (5.1.1)$$

5.1.2. Tiris et al. Model

An analysis of monthly average daily diffuse solar radiation in Gebze, Turkey was presented as follows:

$$H_d = H\left[0.583 + 0.9985\left(\frac{H}{H_o}\right) - 5.24\left(\frac{H}{H_o}\right)^2 + 5.322\left(\frac{H}{H_o}\right)^3\right] \quad (5.1.2)$$

5.1.3. New Developed Equation A

Third degree of polynomial equation is obtained for Izmir as a function of clearness index.

$$H_d = H\left[1.481 + 1.674\left(\frac{H}{H_o}\right) - 17.99\left(\frac{H}{H_o}\right)^2 + 19.45\left(\frac{H}{H_o}\right)^3\right] \qquad (5.1.3)$$

5.2. H_d as a Function of H and Sunshine Fraction (Group 2)

5.2.1. Barbaro et al.'s Model

Monthly-average diffuse solar radiation was calculated as a function of sunshine duration for Italy was given as:

$$H_d = H\left[0.7434 - 0.8203\left(\frac{S}{S_o}\right) + 0.2454\left(\frac{S}{S_o}\right)^2\right] \qquad (5.2.1)$$

5.2.2. Ulgen and Hepbasli's Model

Using the data available for Ankara, Istanbul and Izmir, Turkey; Ulgen and Hepbasli developed the following equation:

$$H_d = H\left[0.6595 - 0.7841\left(\frac{S}{S_o}\right) + 0.2579\left(\frac{S}{S_o}\right)^2\right] \qquad (5.2.2)$$

5.2.3. New Developed Equation B

Monthly-average diffuse solar radiation was developed as a function of sunshine duration for Izmir, Turkey was given as:

$$H_d = H\left[0.917 - 1.995\left(\frac{S}{S_o}\right) + 1.47\left(\frac{S}{S_o}\right)^2\right] \qquad (5.2.3)$$

5.3. H_d as a Function of H_o and the Clearness Index (Group 3)

5.3.1. Ulgen and Hepbasli's Model

Monthly-average diffuse solar radiation was calculated as a function of clearness index for Ankara, Istanbul and Izmir, Turkey was given as:

$$H_d = H_o \left[0.1155 + 0.1958 \left(\frac{H}{H_o}\right)\right] \quad (5.3.1)$$

5.3.2. Aras et al. Models

The new model developed was based on the average values predicted by the twenty models in the literature, as given in the following:

$$H_d = H_o \left[0.3276 - 0.7515 \left(\frac{H}{H_o}\right) + 1.9883 \left(\frac{H}{H_o}\right)^2 - 1.8497 \left(\frac{H}{H_o}\right)^3 \right] \quad (5.3.2)$$

5.3.3. New Developed Equation C

Using regional data, an equation has been developed that was given by;

$$H_d = H_o \left[0.514 - 0.619 \left(\frac{H}{H_o}\right)\right] \quad (5.3.3)$$

5.4. H_d as a Function of H_o and Sunshine Fraction (Group 4)

5.4.1. Ulgen and Hepbasli's Model

Using regional data for 3 big Cities of Turkey, an equation has been developed that was given by;

$$H_d = H_o \left[0.1677 - 0.0926 \left(\frac{S}{S_o}\right)\right] \quad (5.4.1)$$

5.4.2. Aras et al. Model

Monthly-average diffuse solar radiation was calculated as a function of clearness index for CAR of Turkey was given as:

$$H_d = H_o\left[0.2427 - 0.0933\left(\frac{S}{S_o}\right) + 0.1846\left(\frac{S}{S_o}\right)^2 - 0.2184\left(\frac{S}{S_o}\right)^3\right] \quad (5.4.2)$$

5.4.3. New Developed Equation D

The model was developed for Izmir, Turkey. The equation is:

$$H_d = H_o\left[0.391 - 0.59\left(\frac{S}{S_o}\right) + 0.318\left(\frac{S}{S_o}\right)^2\right] \quad (5.4.3)$$

CHAPTER 6

RESULTS

6.1. Results for Global Solar Radiation

In the analysis, the data measured at the IZTECH Campus between 2005 and 2007 were used. The equations mentioned in Chapter 1 were calculated in order to estimate the total monthly-average daily global radiation.

Starting from Eq. (1.5), δ values were calculated and varied between -23.44° and 23.44°. In order to estimate S_o, Eqs. (1.6) and (1.2) were used respectively. In Table 3, S_o can be seen for 3-yr period.

Table 3. Monthly-average of the maximum possible daily hours of bright sunshine for 2005-2007

Months	Hour
January	9,65
February	10,55
March	11,72
April	13,14
May	14,17
June	14,63
July	14,39
August	13,45
September	12,21
October	10,94
November	9,79
December	9,36

Table 4 showed the monthly average daily bright sunshine hours for Izmir, Turkey that was derived from measured data in the Solar-Meteorological Station of Solar Energy Institute in Ege University.

Table 4. Average of bright sunshine hours for 2005-2007
(Source: Correspondence with Assist. Prof. Dr. Koray Ülgen)

Months	**hour**
January	3,10
February	4,46
March	6,45
April	6,63
May	8,82
June	10,41
July	12,01
August	10,25
September	9,13
October	7,49
November	4,90
December	3,52

Eqs. (1.3) and (1.4) were calculated and the results of Eq. (1.3) were given in Table 5. H_o values calculated between 11,581.1 (W/m^2) and 4,088.88 (W/m^2). And the graph of H_o was added to the study as Figure 5.

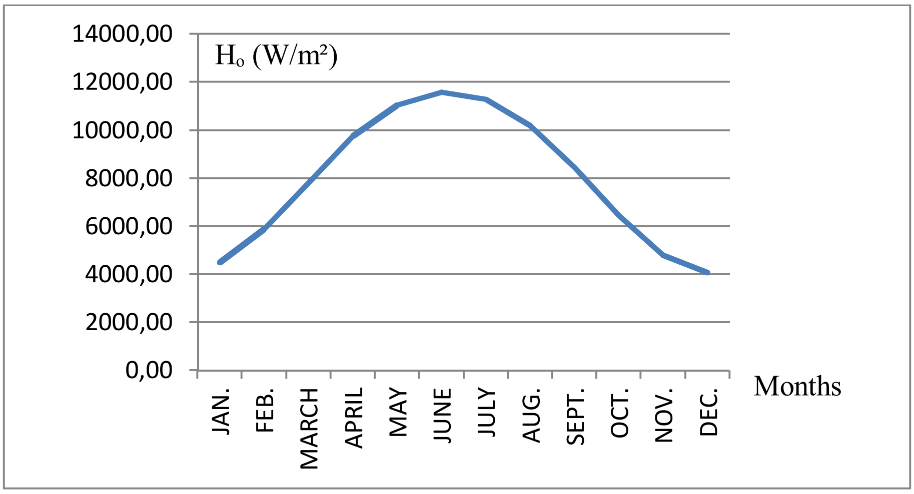


Figure 5. The graph of monthly-average daily extraterrestrial radiation

Table 5. H_o values for Izmir

Months	**H_o(W/m²)**
January	4509,35
February	5886,25
March	7817,24
April	9735,92
May	11054,27
June	11581,10
July	11293,22
August	10198,57
September	8454,53
October	6445,40
November	4808,53
December	4088,88

For each year the monthly average daily global solar radiation is calculated and the tables and figures are given below.

Table 6. The monthly-average hourly global radiation for 2005 (W/m²)

Hour \ Month	**FEB.**	**MARCH**	**APRIL**	**MAY**	**JUNE**	**JULY**	**AUG.**	**SEPT.**	**OCT.**	**NOV.**	**DEC.**
6-7	0	3.23	1.45	14.63	35.41	16.89	2.91	0.06	0.05	0,01	0
7-8	17.77	62.92	46.87	127.76	179.21	139.47	69.91	22.03	8.35	19.67	4.02
8-9	122.5	198.29	221.63	285.82	352.19	306.34	245.28	174.17	96.86	119.86	63.93
9-10	251.83	331.92	391.98	468.55	548.45	481.31	433.3	349.87	255.62	223.03	169.05
10-11	292.27	482.74	568.55	649.28	720.67	655.49	606.58	505.01	380.38	292.53	232.08
11-12	398.22	533.61	668.56	756.22	832.38	773.6	721.93	633.62	488.54	339.3	284.6
12-13	383.44	584.61	725.96	806.13	897.92	849.98	781.65	663.35	545.94	360.86	304.8
13-14	308.55	570.88	754.45	845.89	921.08	892	827.05	685.83	560.03	337.62	268.29
14-15	193.55	551.17	773.41	800.02	886.67	868.63	806.61	644.8	539.76	269.59	231.69
15-16	179.91	401.68	665.71	664.73	807.22	801.65	743.91	558.07	443.46	144.48	129.94
16-17	87.91	272.39	500.42	527.1	694.82	671.85	609.85	426.53	279.07	49.12	32.53
17-18	28.83	116.12	364.56	394.86	520.79	511.73	437.05	277.82	135.69	6.19	0.09
18-19	0.25	20.44	183.07	234.34	339.23	323.27	249.05	99.8	17.2	0	0
19-20	0	1.73	30.35	85.21	153.44	139.18	56.27	6.95	0.02	0	0
20-21	0	0	0	0.29	33390	14.57	13.7	2.69	0	0	0
TOTAL	**2265.03**	**4131.73**	**5896.97**	**6660.83**	**7445.96**	**7896.40**	**6605.05**	**5050.6**	**3750.97**	**2162.26**	**1721.02**

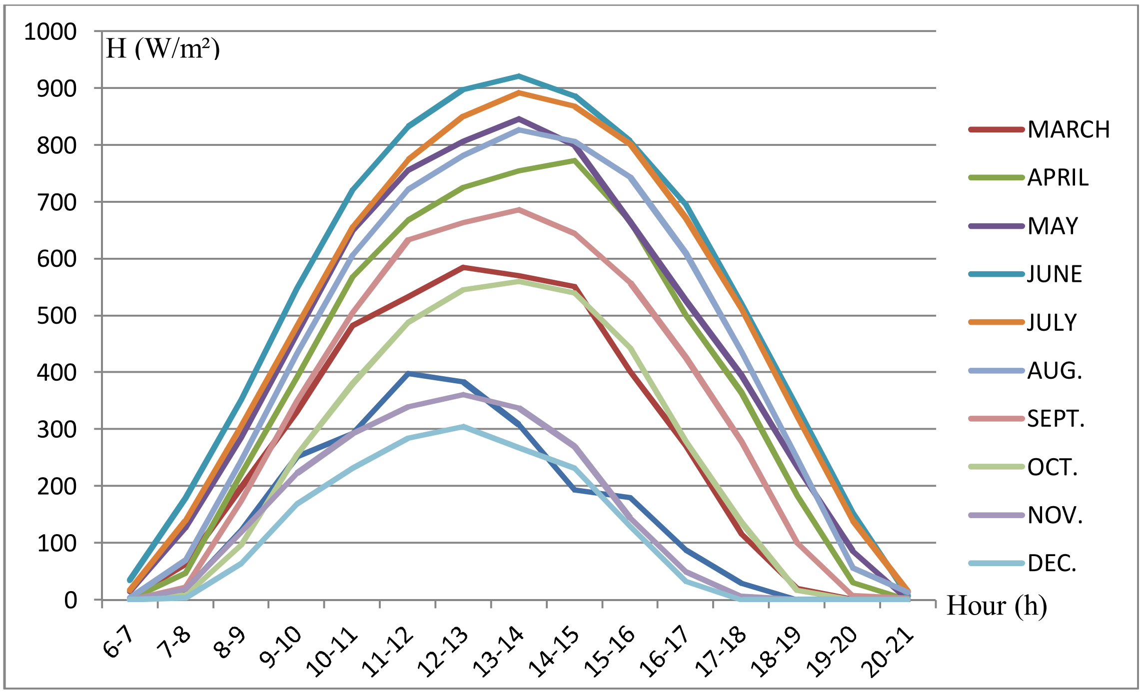


Figure 6. The graph of monthly-average hourly global radiation for 2005

Table 7. The monthly-average hourly global radiation for 2006 (W/m^2)

Hour \ Month	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
6-7	0	0	2.03	0.48	23.14	41.16	21.6	4.05	0.02	0.04	0.1	0
7-8	1.903	12.14	50.85	29.8	145.53	176.48	153.75	100.48	41.35	9.89	34.05	4.94
8-9	51.01	96.63	165.09	128.51	326.6	348.65	318.91	265.04	177.62	96.86	155.01	80.41
9-10	169.521	209.05	322.88	228.87	525,39	518,84	484,33	451,85	341,1	230,77	289,18	198,62
10-11	291.586	296.041	421.88	392.37	661.51	666.09	647.35	606.48	507.71	351.87	390.43	285.01
11-12	376.892	370.732	504.89	529.08	756.23	782.05	790.85	710.47	634.23	438.33	452.58	327.19
12-13	403.709	422.107	549.59	700.37	827.57	874.4	866.59	765.81	685.47	496.4	459.86	326.72
13-14	350.666	397.553	533.81	763.05	838.64	906.19	890.8	796.45	693,56	516,39	397,37	299,05
14-15	303.478	322.898	489.28	710.76	820.2	845.28	862.07	792.8	614,88	464,77	300,46	234,06
15-16	210.505	255.93	347.33	622.94	739.19	778.88	777.9	723.94	539.62	363.37	180.87	136.81
16-17	98.021	135.82	267.86	510.65	615.67	622.97	650.39	584.75	420.85	240	43.5	30.23
17-18	22.618	31.22	147.43	395.53	467.98	480.63	489.64	417.56	265.32	130.4	1.03	0.21
18-19	13	0.19	42.49	238.08	282.06	305.85	305.89	238.56	107.46	18.65	0	0
19-20	0	0	0	109.75	104	138.39	117.16	67.3	6.15	0.01	0	0
20-21	0	0	0	0	24.69	13.16	13.29	2.5	0	0	0	0
TOTAL	**2292.909**	**2550.311**	**3845.41**	**5360.24**	**7158.4**	**7499.02**	**7390.52**	**6528.04**	**5035.34**	**3357.75**	**2704.44**	**1923.25**

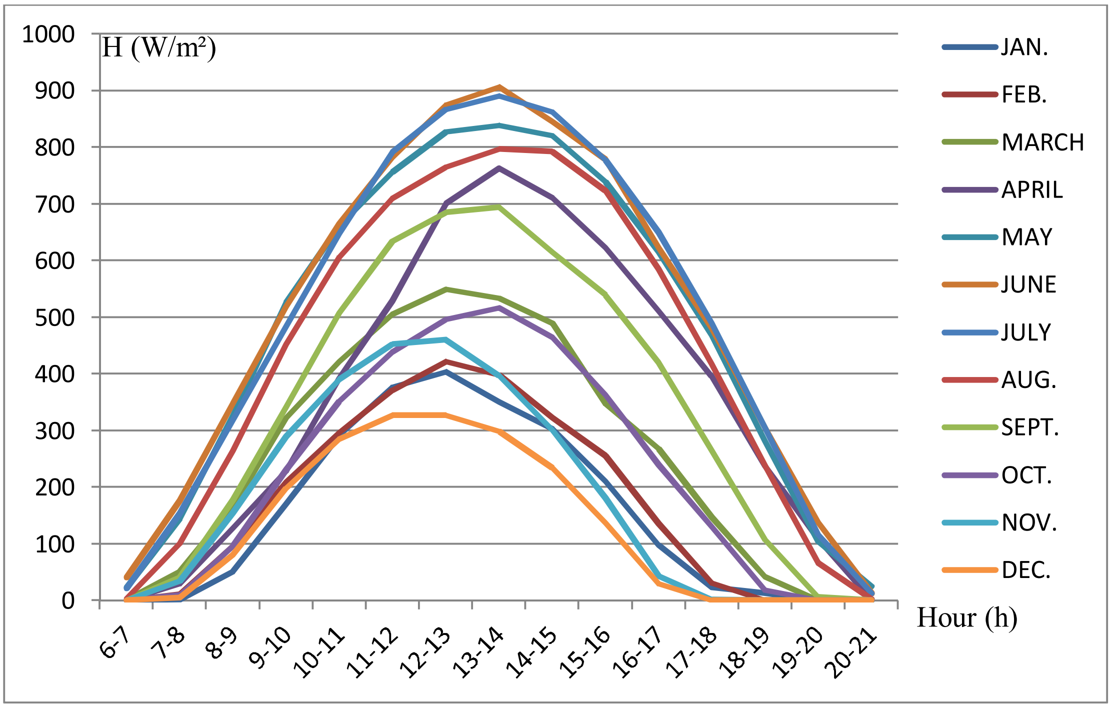


Figure 7. The graph of monthly-average hourly global radiation for 2006

Table 8. The monthly-average hourly global radiation for 2007 (W/m²)

Hour \ Month	JAN.	FEB.	MARCH	APRIL	MAY
6-7	0	0.16	4.53	5.48	35.76
7-8	7.77	30.44	77.09	87.83	174.14
8-9	87.3	140.91	211.72	247.48	319.83
9-10	202.9	265.83	369.73	426.88	495.32
10-11	314.4	406.33	533.33	608.294	600.07
11-12	397.17	470.68	610.97	704.58	710.38
12-13	420.31	464.14	640.09	771.41	771.13
13-14	398.01	430.09	566.66	790.04	710.11
14-15	315.06	322.64	519.7	748.53	672.48
15-16	197.39	220.41	399.54	653.43	620.41
16-17	59.66	117.16	276.42	484.75	505.45
17-18	2.07	19.73	150.39	334.28	370.92
18-19	0	0.69	59.69	152.63	208.38
19-20	0	0	3.64	14.67	48.85
20-21	0	0	0	0	1.14
TOTAL	**2402.04**	**2889.21**	**4423.5**	**6030.28**	**6244.37**

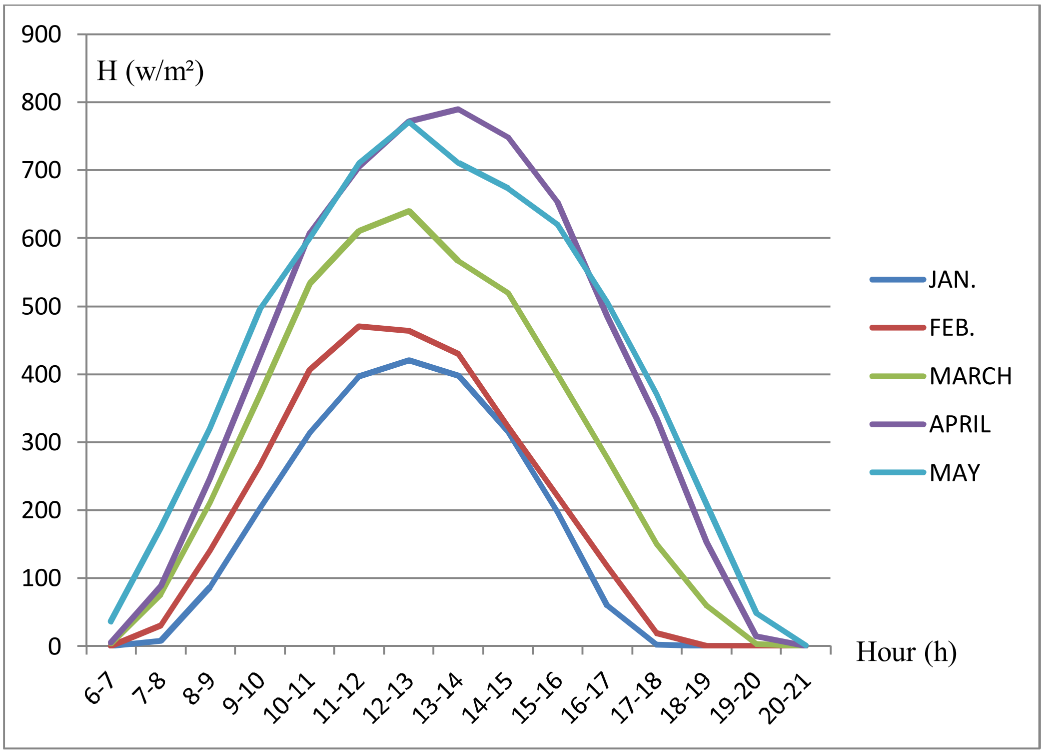


Figure 8. The graph of monthly-average hourly global radiation for 2007

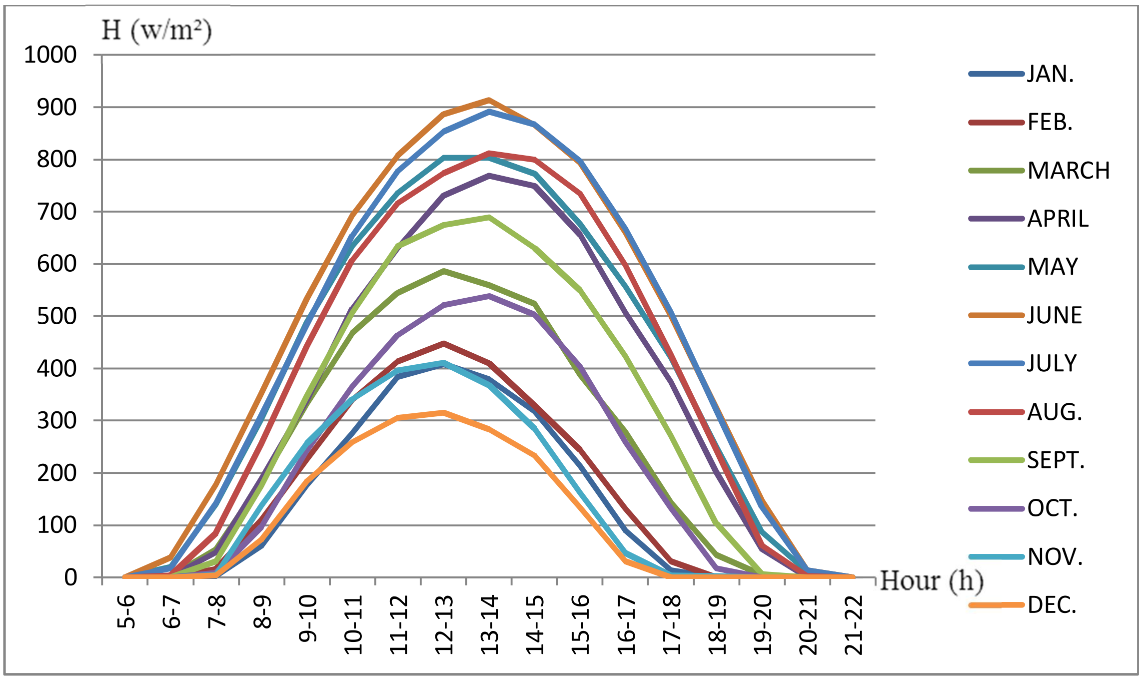


Figure 9. The graph of monthly-average hourly global radiation for 3 years period

According to Table 9 the maximum value of the monthly-average daily global radiation for the average of 2005, 2006 and 2007 was recorded to be 7,702.66W/m² in June. The minimum value of H was 1,822.15W/m² observed during December. The highest value was recorded between 13 -14 pm. The graph for the average of the 3 years was shown in Figure 9. As for each month, the monthly-average hourly global solar radiation tables were attached in Appendix A.

The models used to estimate the monthly-average daily global radiation on a horizontal surface (H) were categorized in 4 groups, as seen from Eq. (4.1) to Eq. (4.14). These groups consisted of the relations gained from Angstrom-type equations. The types of the models and the calculated results were illustrated below in Table 10. The regression coefficients "a and b" of the Angstrom-type correlation for the monthly average daily global solar radiation of Eq. (4.2) and Eq. (4.3) were determined as given in Table 11.

The comparison of solar radiation models can be seen in Figure 10. The results are close to each other. To analyze the comparison in detail, statistical equations have been referred. Values of MBE, RMSE and t-stat of selected models were shown in Table 12. The error percentages of the models were also added in the table.

Table 9. Hourly average global solar radiations for the average of 3 years (W/m²)

Hour / Month	January	February	March	April	May	June	July	August	September	October	November	December
5-6	0	0	0	0	0	0	0	0	0	0	0	0
6-7	0	0.01	2.39	1.38	19.86	38.29	17.86	3.48	0.01	0.05	0.05	0
7-8	2.55	15.71	54.86	47.69	140	177.84	142.4	85.2	31.53	9.11	5.6	4.48
8-9	60.37	109.98	182.72	189.66	302.88	350.42	308.92	255.16	175.87	96.86	137.44	72.17
9-10	176.69	225.66	332.93	338.43	488.65	533.64	481.93	442.57	345.52	243.29	255.92	183.84
10-11	276.65	339.39	467.79	513.97	633.82	693.38	653.9	606.53	506.34	366.12	341.48	258.55
11-12	383.36	412.97	544.13	630.51	736.25	807.22	776.78	716.2	633.93	463.44	395.94	305.9
12-13	408.87	447.36	586.55	730.28	802.99	886.16	853.04	773.73	674.25	521.23	410.36	315.76
13-14	378.56	409.38	559.16	769.15	803.03	913.99	891.78	811.75	689.63	538.27	367.5	283.67
14-15	318.35	328.88	523.69	748.74	772.69	865.98	867.42	799.7	629.84	502.27	285.02	232.88
15-16	214.06	244.53	387.89	655.67	675.5	793.05	797.27	733.93	548.85	403.41	162.67	133.37
16-17	89.62	131.81	278.43	506.81	556.79	659.67	667.59	597.3	423.69	259.53	46.31	31.38
17-18	13.77	30.42	143.99	373.6	420.73	500.71	507.2	427.3	271.57	133.07	3.61	0.15
18-19	0.29	0.64	43.19	202.6	250.89	322.54	319.71	243.81	103.63	17.92	2.43	0
19-20	0	0	5.23	54.33	87.55	145.91	134.66	61.79	6.22	0.02	0	0
20-21	0	0	0	0	11.91	13.86	13.62	2.59	0	0	0	0
21-22	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL	**2323.14**	**2696.74**	**4112.95**	**5762.82**	**6703.54**	**7702.66**	**7434.08**	**6561.04**	**5040.88**	**3554.59**	**2414.33**	**1822.15**

Table 10. Hourly average global solar radiation values for solar radiation models (W/m²)

Months \ Model Eq.No	**4.1**	**4.2**	**4.3**	**4.4**	**4.5**	**4.6**	**4.7**	**4.8**	**4.9**	**4.10**	**4.11**	**4.12**
	Group 1	Group 3	Group 3	Group 3	Group 3	Group 3	Group 2	Group 4	Group 4	Group 2	Group 3	Group 4
January	1572.15	1748.23	1793.03	2220.00	1598.85	1693.13	2084.81	1769.95	1877.67	1928.11	1917.82	1975.15
February	2398.67	2660.35	2679.41	3150.24	2449.02	2628.44	2988.16	2636.94	2757.75	2821.05	2828.28	2731.78
March	3729.34	4103.26	4093.88	4583.46	3840.91	4102.41	4415.36	4044.53	4174.50	4256.14	4281.05	4028.46
April	4596.48	4867.20	4865.93	5534.50	4525.05	4851.76	5300.52	4799.38	4975.10	5074.36	5101.66	4810.27
May	5798.08	6218.35	6199.26	6788.38	5894.56	6232.67	6605.14	6136.85	6292.42	6430.70	6464.60	6167.30
June	6483.62	6998.86	6994.32	7486.60	6753.14	7015.04	7380.92	6922.29	7040.24	7262.85	7282.59	7257.26
July	6836.55	7399.16	7456.47	7779.03	7345.83	7383.41	7823.01	7317.43	7345.74	7795.65	7768.38	8584.20
August	5860.89	6389.46	6403.43	6776.30	6235.42	6396.10	6734.60	6323.76	6398.95	6663.57	6666.70	6897.25
September	4745.82	5242.87	5249.43	5573.16	5099.02	5250.76	5525.58	5188.38	5258.14	5458.65	5465.12	5587.19
October	3380.70	3816.59	3809.98	4104.58	3661.93	3826.60	4030.13	3772.58	3846.56	3953.52	3968.08	3890.89
November	2076.92	2394.31	2394.19	2726.69	2224.89	2386.03	2610.27	2361.15	2448.46	2497.50	2510.77	2368.54
December	1506.15	1730.63	1754.97	2109.12	1586.95	1696.90	1990.91	1727.47	1817.36	1862.92	1862.26	1843.97

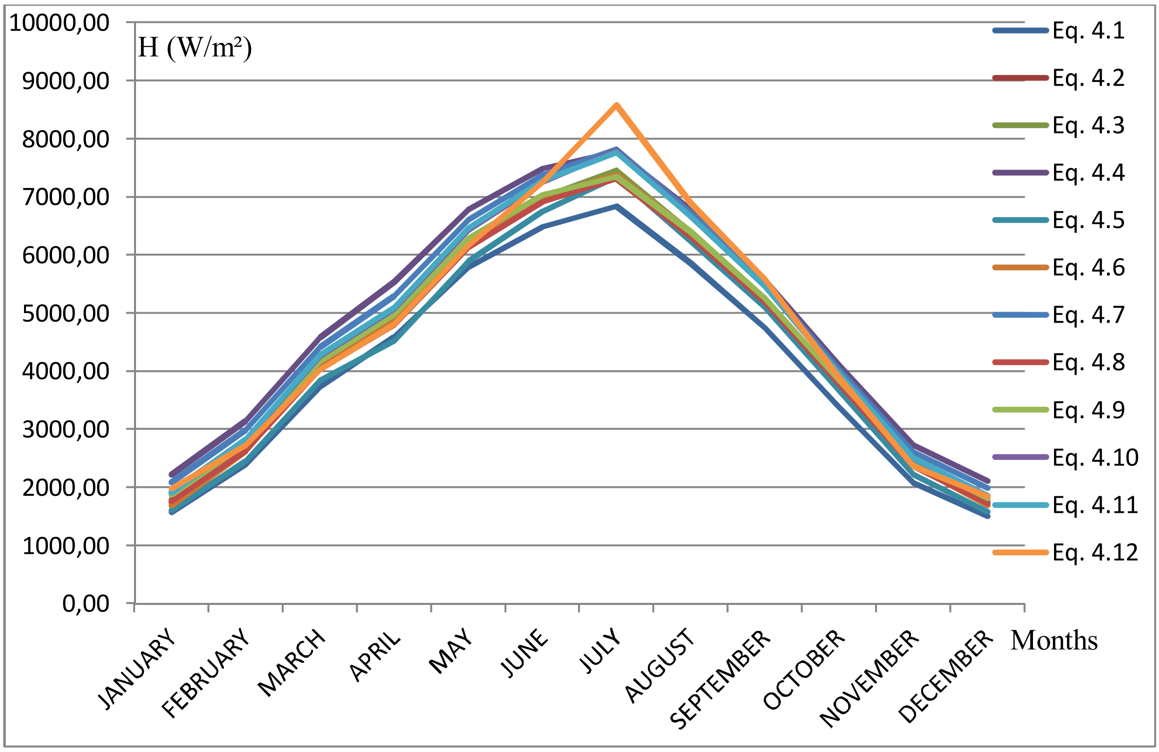


Figure 10. The graph of solar radiation models

Table 11. Correlation coefficients of “a, b”

Months	a	b
January	0.204	0.449
February	0.225	0.431
March	0.253	0.408
April	0.276	0.389
May	0.289	0.378
June	0.294	0.374
July	0.292	0.376
August	0.282	0.384
September	0.262	0.400
October	0.235	0.423
November	0.209	0.444
December	0.197	0.454

The following main results were obtained from the evaluation of the values presented in Table 12:

Evaluation of Group 1:

There is only one equation in this group. The results for MBE = -595.294 W/h, RMSE = 685.838 W/h, t-stat=5.797 and e=-12.727 were obtained from Eq. 4.1.

Evaluation of Group 2:

There are two equations in this section. They were Eqs. 4.7 and 4.10. The best results for MBE = -10.324 W/h, t-stat=0.100 and e=-0.2207 were obtained from Eq. 4.10 and best results for RMSE = 325.248 W/h from Eq. 4.7.

Evaluation of Group 3:

Six models were compared in this part. The best results for MBE = -0.968 W/h, RMSE = 337.305 W/h, t-stat=0.010 and e=-0.0207 were obtained from the new developed model Eq. 4.11.

Evaluation of Group 4:

There were also two models in this group. The best results for MBE = 1.112 W/h, t-stat=0.007 and e=0.02377 were obtained from the new developed Eq. 4.12 and the best result RMSE = 440.037 W/h was obtained from Eq. 4.8.

Among the solar radiation models, for all test methods, the author's model given by Eq. (4.14) was found to be the most accurate model, followed by Eq. (4.13) and Eq. (4.12) respectively. By looking at the relative percentage errors, it has seen that the new developed models gave the closest values rather than the other models. They were followed by Eq. (4.9) and Eq. (4.7).

Table 12. Comparison of statistical methods for global solar radiation models

Method / Model	MBE (W/m²)	RMSE (W/m²)	t-stat	e%
1	-595,294	685,838	5,797	-12,727
2	-213,304	409,644	2,023	-4,5603
3	-202,884	406,316	1,911	-4,3375
4	225,261	350,564	2,781	4,81593
5	-409,445	575,035	3,363	-8,7537
6	-222,139	417,388	2,085	-4,7492
7	113,374	325,248	1,233	2,42385
8	-260,684	440,037	2,439	-5,5733
9	-158,001	365,375	1,591	-3,378
10	-10,324	343,676	0,100	-0,2207
11	-0,968	337,305	0,010	-0,0207
12	1,112	530,150	0,007	0,02377

6.2. Results for Diffuse Solar Radiation

The data used for diffuse solar radiation calculations are performed for 19 months period between 2004 and 2005. The average of this data is shown in Table 13.

Using the H and H_o values that were calculated and measured in the previous section, statistical methods were applied to the models, which were used to estimate the monthly-average daily diffuse solar radiation.

Table 13. Measured diffuse solar radiation data

Months	2004-2005
January	632.3595
February	542.341
March	1578.86
April	1765.674
May	1797.517
June	1336.541
July	1433.864
August	1277.589
September	1224.271
October	1130.865
November	1244.644
December	752.2009

In Table 13, H_d values measured between 542.34 (W/m^2) and 1,797.51 (W/m^2). The graph of H_d was added to this thesis study as Figure 11.

The models used to estimate the monthly-average daily diffuse radiation on a horizontal surface H_d were categorized in four groups. In the first group k_d is calculated as a function of clearness index. In the second group k_d is calculated as a function of sunshine duration. In the third group k_{dd} is calculated as a function of clearness index and in the last group k_{dd} is calculated as a function of sunshine duration. H_d calculations were done according to these groups. In the Table 14, the H_d values were given for each model.

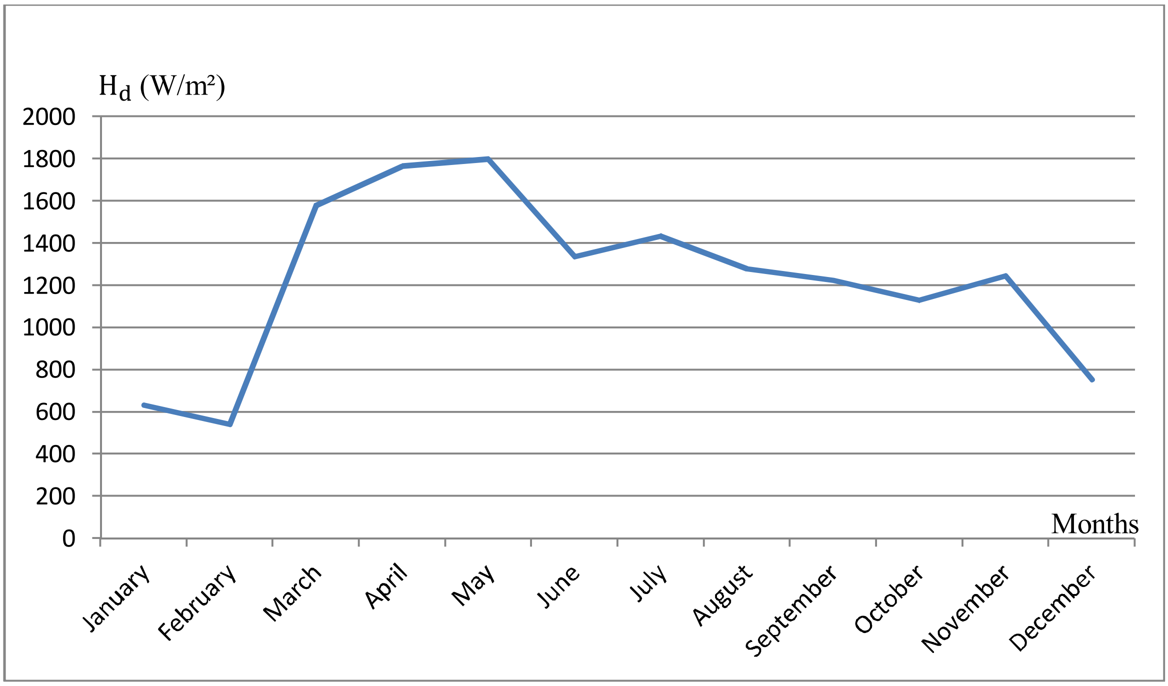


Figure 11. The graph of H_d

For each group, one new model was evaluated due to the measured data for Izmir. The Eqs. 5.1.3, 5.2.3, 5.3.3 and 5.4.3 are the new equations to estimate the monthly-average daily diffuse radiation. In Figure 12 all the new equations were graphed and installed in one drawing. With this kind of graph, it was easily found the values of k_d, k_{dd}, k_t and S/S_0.

Table 14. The monthly-average daily diffuse solar radiation for models

Months / Models	January	February	March	April	May	June	July	August	September	October	November	December
5.1.1	1077.52	1416.90	1854.71	2126.50	2349.99	2158.94	2139.66	2001.51	1832.35	1493.27	1155.95	979.66
5.1.2	1009.07	1219.95	1780.64	2546.17	3005.70	3812.44	3625.98	3107.89	2236.07	1537.81	1055.03	835.17
5.1.3	530.03	923.01	882.47	1166.81	1460.83	2763.78	2494.10	1909.60	1040.08	693.35	599.19	684.49
5.2.1	1173.36	1188.45	1507.90	2259.80	2197.68	2188.57	1707.82	1709.89	1347.97	1055.56	951.64	855.58
5.2.2	1008.48	1009.44	1260.21	1899.82	1818.79	1789.32	1373.42	1388.19	1096.61	866.20	800.41	730.74
5.2.3	993.39	907.73	1088.00	1641.09	1640.63	1861.65	2051.02	1643.35	1245.50	853.72	691.95	682.46
5.3.1	975.70	1207.88	1708.21	2252.86	2589.32	2845.80	2759.96	2462.59	1963.50	1440.43	1028.11	829.04
5.3.2	970.59	1311.27	1666.71	1906.33	2106.55	1888.99	1884.43	1780.12	1642.73	1338.24	1045.34	915.36
5.3.3	879.78	1356.25	1472.14	1437.08	1532.40	1184.74	1203.02	1180.78	1225.32	1112.65	977.11	973.77
5.4.1	621.99	756.90	913.02	1178.07	1216.56	1179.46	1021.13	990.24	832.72	672.44	583.42	543.27
5.4.2	1012.48	1293.61	1648.77	2089.19	2249.18	2213.77	1879.86	1856.87	1563.34	1258.83	1033.09	908.14
5.4.3	1056.11	1168.58	1272.35	1697.33	1624.37	1531.48	1356.24	1285.18	1079.44	877.63	842.90	875.24

The following main results were obtained from the evaluation of the values presented in Table 15:

Evaluation of Group 1:

The best results for MBE = 35.918 W/h, t-stat=0.179 and e=2.929 were obtained from the new model Eq. 5.1.3, while best result for RMSE = 557.806 W/h was calculated from the Eq. 5.1.1.

Evaluation of Group 2:

The best results for MBE = 27.077 W/h, RMSE = 286.456 W/h, t-stat=0.315 and e=2.208 were obtained from Eq. 5.2.2. The new developed model's values are also very close to the best results.

Evaluation of Group3:

The best results for MBE = -15.140 W/h, RMSE = 305.507 W/h, t-stat=0.165 and e=-1.234 were obtained from the new model (Eq. 5.3.3).

Evaluation of Group 4:

The best results for MBE = -4.156 W/h, RMSE = 289.548 W/h, t-stat=0.048 and e=-0.339 were obtained from the new developed (Eq. 5.4.3).

Among the diffuse solar radiation models, for MSE, t-stat and e methods, the author's model given by Eq. (5.4.3) was found to be the most accurate model. For RMSE, Eq. (5.2.2) gave the best results. They were followed by Eq. (5.3.3) and Eq. (5.2.3) respectively.

Table 15. Comparison of statistical methods for diffuse solar radiation

Method / Model	MBE (W/m^2)	RMSE (W/m^2)	t-stat	e%
5.1.1	489.186	557.806	6.053	39.888
5.1.2	921.266	1232.486	3.732	75.120
5.1.3	35.918	665.798	0.179	2.929
5.2.1	285.625	430.587	2.940	23.290
5.2.2	27.077	286.456	0.315	2.208
5.2.3	48.648	378.915	0.429	3.967
5.3.1	612.223	794.646	4.008	49.921
5.3.2	311.663	395.166	4.255	25.413
5.3.3	-15.140	305.507	0.165	-1.234
5.4.1	-350.626	437.246	4.451	-28.590
5.4.2	357.533	458.881	4.122	29.153
5.4.3	-4.156	289.548	0.048	-0.339

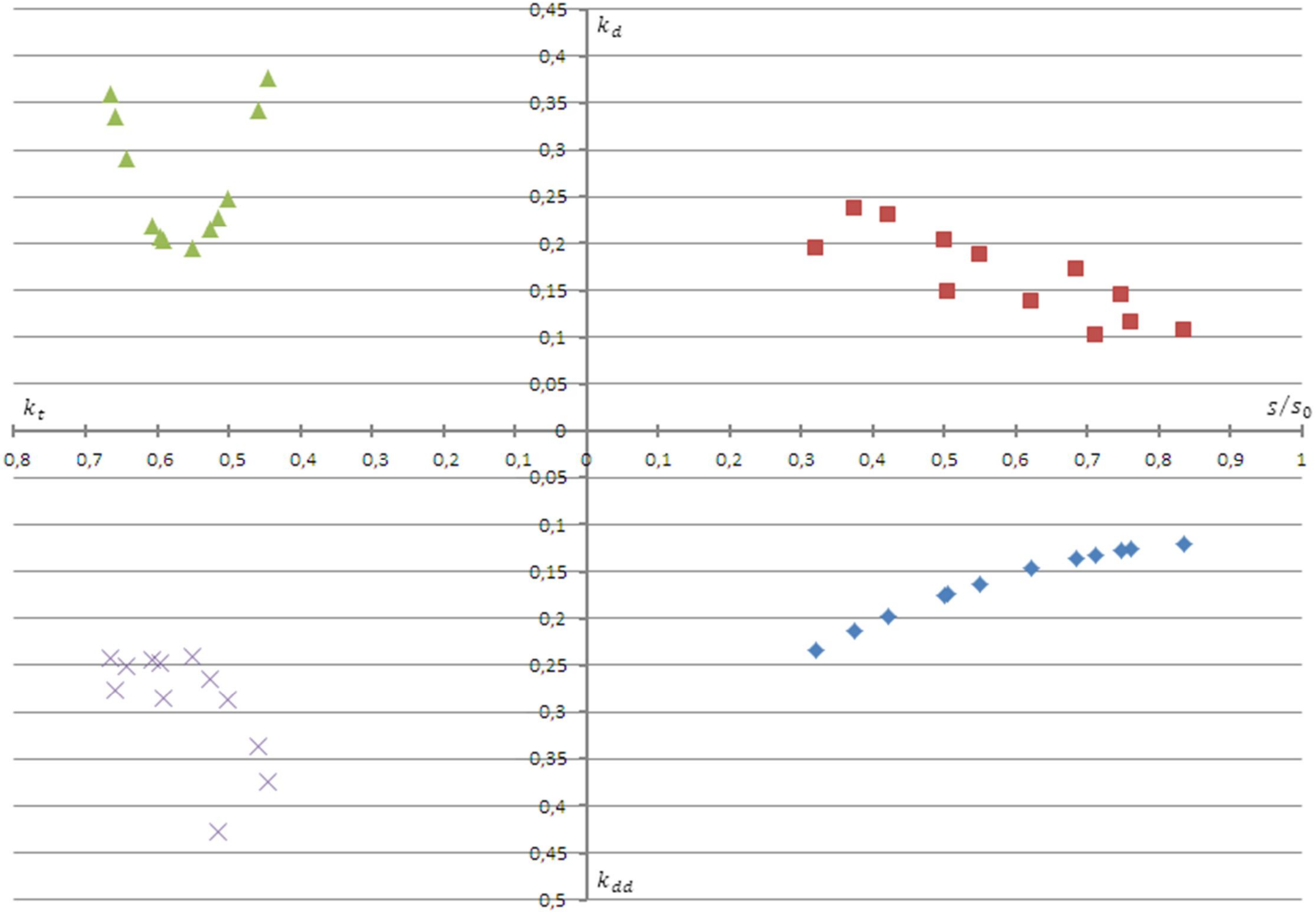


Figure 12. The graph of new developed equations for diffuse solar radiation

CHAPTER 7

CONCLUSION

In this thesis, firstly solar radiation models for predicting the average daily and hourly global and diffuse radiations on horizontal surface are reviewed. Then data of global and diffuse solar radiations are analyzed from February, 2005 to May, 2007 and from February, 2004 to December, 2005 on the campus area of IZTECH, respectively. Empirical correlations are developed to estimate the monthly-average daily global and diffuse radiations on a horizontal surface for Izmir, Turkey. 3 new models are developed for estimating the monthly-average daily global solar radiation, whereas 4 new models are developed for estimating the monthly-average daily diffuse solar radiation. The developed models are compared with the models form the literature on the basis of statistical methods namely, RMSE, MBE, T-stat and "e".

It is concluded that, the third-order polynomial equation gave the closest results to the measured data for global solar radiation. The developed model given by Eq. (4.14) is found to be the most accurate model for all test methods. For diffuse part, it is concluded that the new models developed during this study are found to be reasonably good for Izmir, Turkey comparing to the previous studies. The eq. (5.4.3) is found to have the best results for MBE, t-stat and "e" methods. In RMSE the eq. (5.2.2) gave the closest result according to the measured data.

It can be deduced from the results that the new developed correlations are found to be reasonably reliable for estimating or predicting the daily global and diffuse radiations for Izmir, Turkey and, possibly, elsewhere with similar climatic condition.

LIST OF REFERENCES

Akinoglu, B. G. and Ecevit, A. (1990). Construction of a quadratic model using modified Angstrom coefficients to estimate global solar radiation. Solar Energy 45(2):85–92.

Akpabio, L. E.; Udo S. O.; Etuk S. E. (2004), Empirical correlation of global solar radiation with Meteorological data for Onne, Nigeria. Turkish J.Physics, 28: 222-227.

Aksoy, B. (1997), Estimated monthly average global radiation for Turkey and its comparison with observations, Renewable Energy, 10: 625-633

Angstrom, A. (1924), Solar and terrestrial radiation. Quart. Journal of the Royal Meteorological Society, 50:121–125.

Aras, H.; Balli, O.; Hepbasli, A. (2006), Global Solar Potential. Part 1: Model Development, Energy Sources, Part B, 1(3):303-315

Barbaro S.; Cannato G.; Coppolina S.; Leone C; Sinagra E.(1981), Diffuse solar radiation statistics for Italy. Solar Energy, 26:429–35

Che H. Z.; Shi G. Y.; Zhang X. Y.; Zhao J. Q.; Li Y. (2007), Analysis of sky condition using 40 years records of solar radiation data in china. Theoretical and applied climatology, 89: 83-94

Correspondence with Koray Ülgen.

Diez-Mediavilla, M.; De Miguel, A.; Bilbao J (2005), Measurement and comparison of diffuse solar irradiance models on inclined surfaces in Valladolid (Spain).Energy Conversion and Management, 46: 2075-2092

El-Sebaii, A. A.; Al-Ghamdi, F. S.; Al-Hazmi and Adel S. Faidah (2009), Estimation of global solar radiation on horizontal surfaces in Jeddah, Saudi Arabia. Energy Policy, 37: 3654-3649

Gunes, M. (2001), Analysis of daily total horizontal solar radiation measurements in Turkey. Energy Sources 23:563–570.

Haydar A.; Balli O.; Hepbasli A. (2006), Estimating the horizontal diffuse solar radiation over the Central Anatolia region of Turkey. Energy Convers Manage, 47:2240–9

Haydar A.; Balli O.; Hepbasli A. (2006), Global solar radiation potential, Part 2: Statistical analysis. Energy Sources, 1:317–26

Inforse, (June,2011) http://www.inforse.dk/europe/dieret/Solar/solar.html

Kaygusuz K.; Ayhan T. (1999), Analysis of solar radiation data for Trabzon, Turkey. Energy Convers Manage, 40:545–56

Kaygusuz, K. (1999),The comparison of measured and calculated solar radiations in Trabzon, Turkey. Energy Sources, 21:347–353

Kilic, A. ve Öztürk, A. (1983), Güneş Enerjisi, Kipaş Dağıtımcılık, İstanbul

Kipp & Zonen, Pyranometer Instruction Manual (2000)

Liu R. Y. H.; Jordan R. C. (1960), The interrelationship and characteristics distribution of direct, diffuse and total solar radiation. Solar Energy, 4(3):1–19

Ogelman, H.; Ecevit, A. and Tasdemiroglu, E. (1984), A new method for estimating solar radiation from bright sunshine data. Solar Energy, 33: 619-625

Ogulata, R. T. and Ogulata, S. N. (2002), Solar radiation on Adana, Turkey. Applied Energy, 71: 351–358

REN21 (2008). Global Status Report 2007 REN21 Secretariat, 51 pages.

REN21 (2010). Renewables 2010 Global Status Report, p. 15-16.

Sen, Z. and Tan, E. (2001), Simple models of solar radiation data for northwestern part of Turkey. Energy Convers Manage, 42:587–598.

Stone R. J. (1993) Improved statistical procedure for the evaluation of solar radiation estimation models. Solar Energy, 51(4):288–91

Tarhan, S.; Sari, A. (2005), Model selection for global and diffuse radiation over the Central Black Sea (CBS) region of Turkey. Energy Convers Manage, 46:605–13

Tasdemiroglu, E. and Sever, R. 1986. Monthly and yearly average maps of total and direct solar radiation in Turkey. Solar Energy 37:205–213.

Tasdemiroglu E.; Sever, R. (1991), Estimation of monthly average daily, horizontal diffuse radiation in Turkey. Energy, 16(4):787–90

Tiris, M.; Tiris, C. and Ture, I. E. (1996), Correlations of monthly-average daily global, diffuse and beam radiations with hours of bright sunshine in Gebze, Turkey. Energy Convers Manage, 37(9): 1417–1421

Togrul, I. T. and E. Onat (1999), A study for estimating solar radiation in Elazig using geographical and meteorological data. Energy Convers Manage, 40: 1577–1584

Togrul, İ. T. and Togrul, H. (2002), Global solar radiation over Turkey: Comparison of predicted and measured data, Renewable Energy, 25: 55-67

Turkish Electrical Works Research Directorate http://www.eie.gov.tr/turkce/YEK/gunes/tgunes.html

Ulgen, K. and Hepbasli, A. (2004), Solar radiation models. Part 2: Comparison and developing new models, Energy Sources, 26: 521-530

Ulgen, K. ve Ozbalta, N., Measurement and evaluation of total solar radiation on horizantol surfaces in Bornova, Izmir, 12. Ulusal Isı Bilimi ve Tekniği Kongresi

Ulgen, K. and Hepbasli, A. (2002), Comparison of solar radiation correlations for Izmir, Turkey. International Journal of Energy Research, 26: 413–430

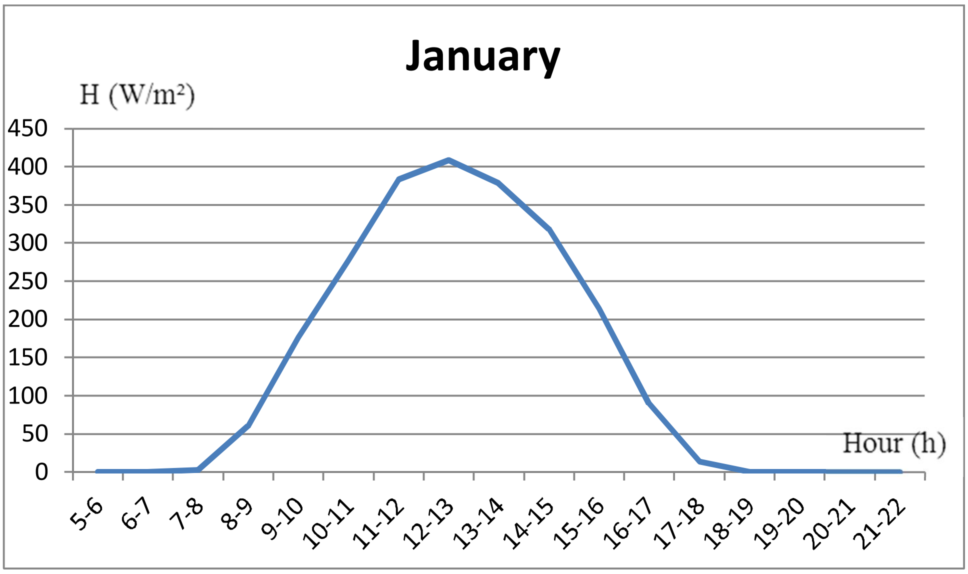
Ulgen, K. and Hepbasli, A. (2002), Solar Radiation Models. Part 1: A Review. Energy Sources, 26: 413-430

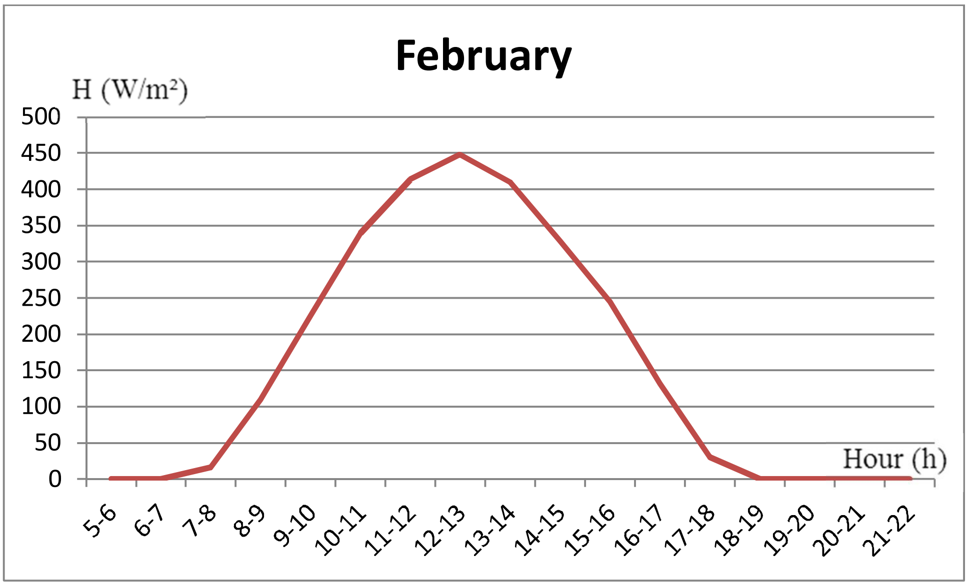
Yildiz, M. and Oz, S. (1994), Evaluation of the solar energy potential of Turkey. In Proc. of the 6th National Energy Congress. Izmir, p. 250–260 (in Turkish).

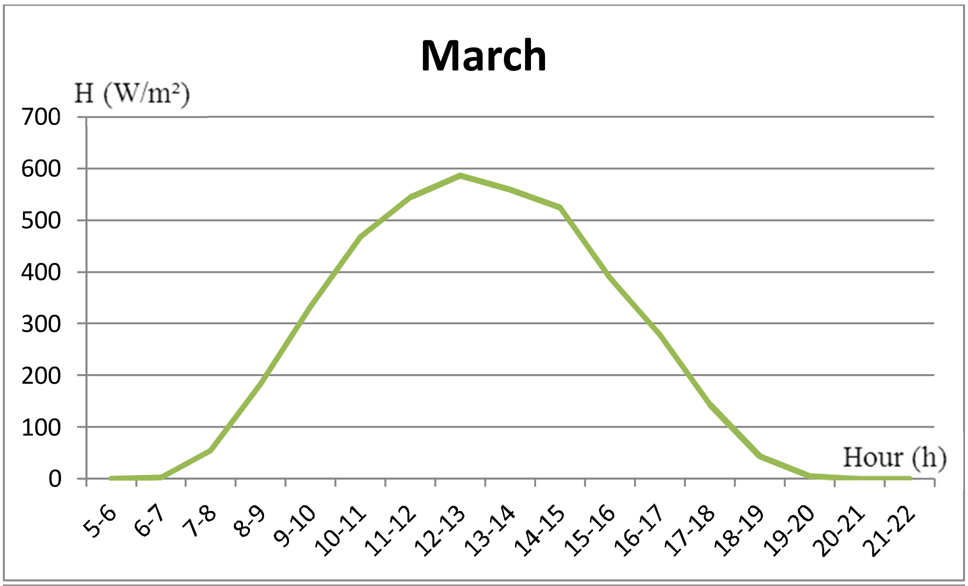
Yingni Jiang (2009) Estimation of monthly mean daily diffuse radiation in China. Applied Energy, 86:1458–1464

APPENDIX A

The monthly-average hourly global solar radiation tables






March
H (W/m²)
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
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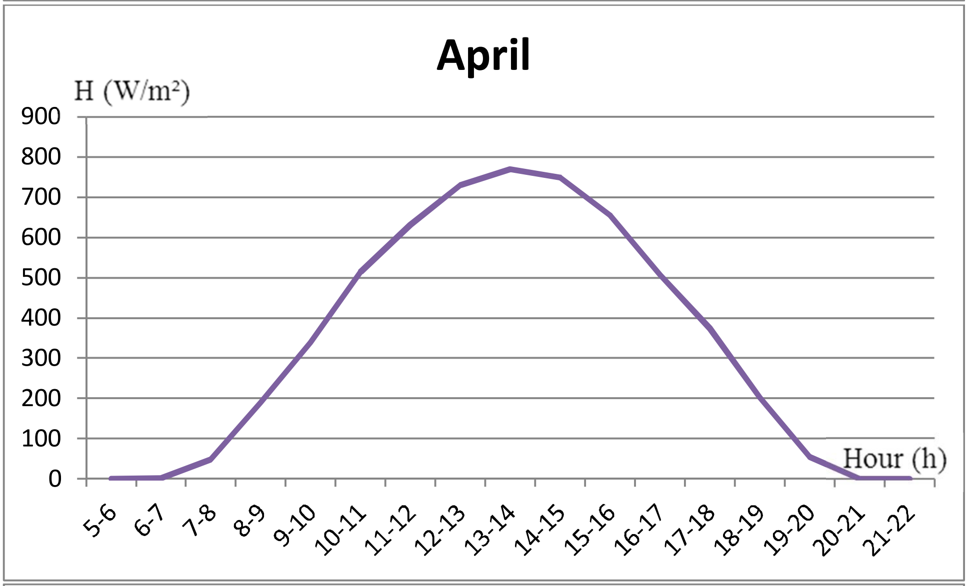
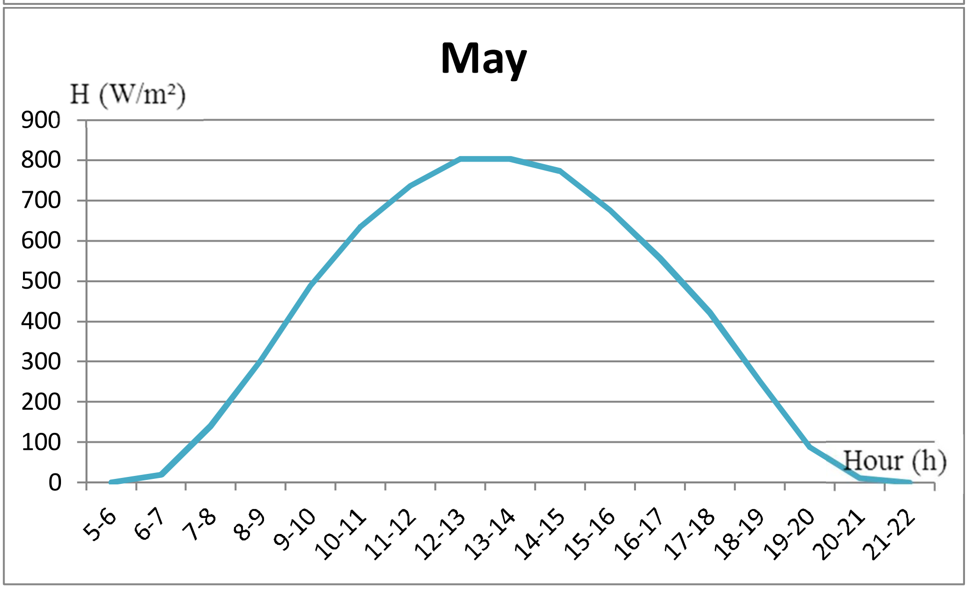
18-19
19-20
20-21
21-22


April
H (W/m²)
900
800
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22


May
H (W/m²)
900
800
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
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15-16
16-17
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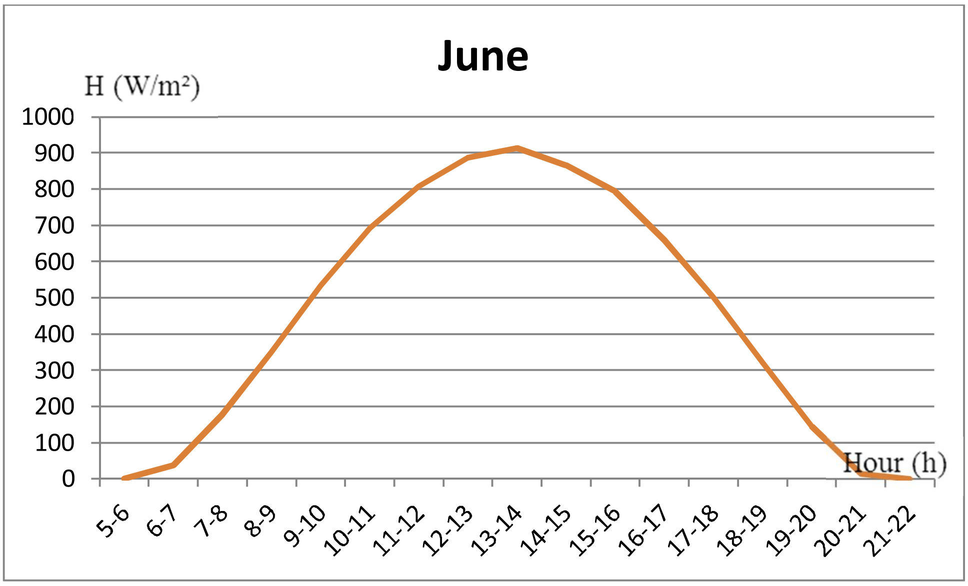
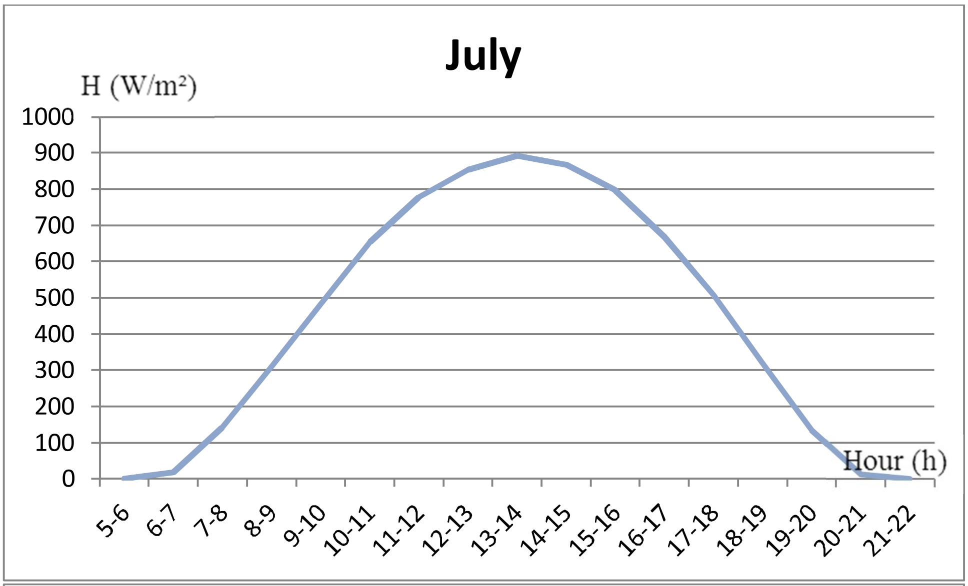
18-19
19-20
20-21
21-22


June
H (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22


July
H (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
17-18
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19-20
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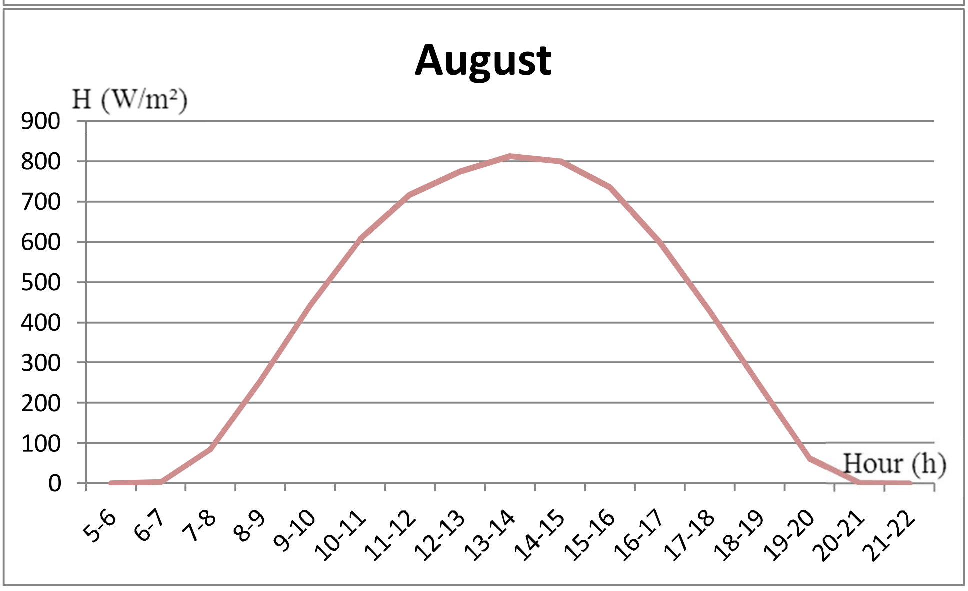
21-22


August
H (W/m²)
900
800
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
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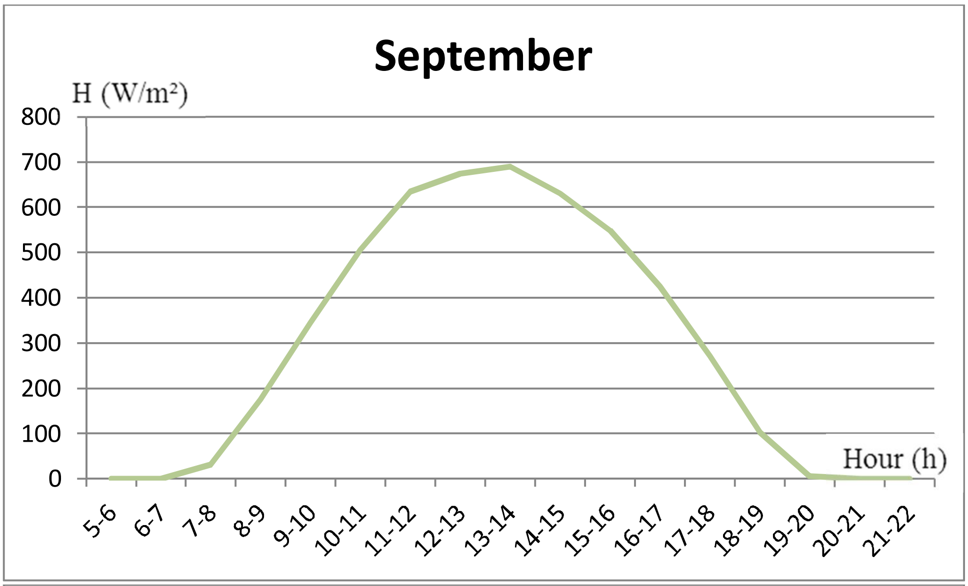
21-22


September
H (W/m²)
800
700
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
16-17
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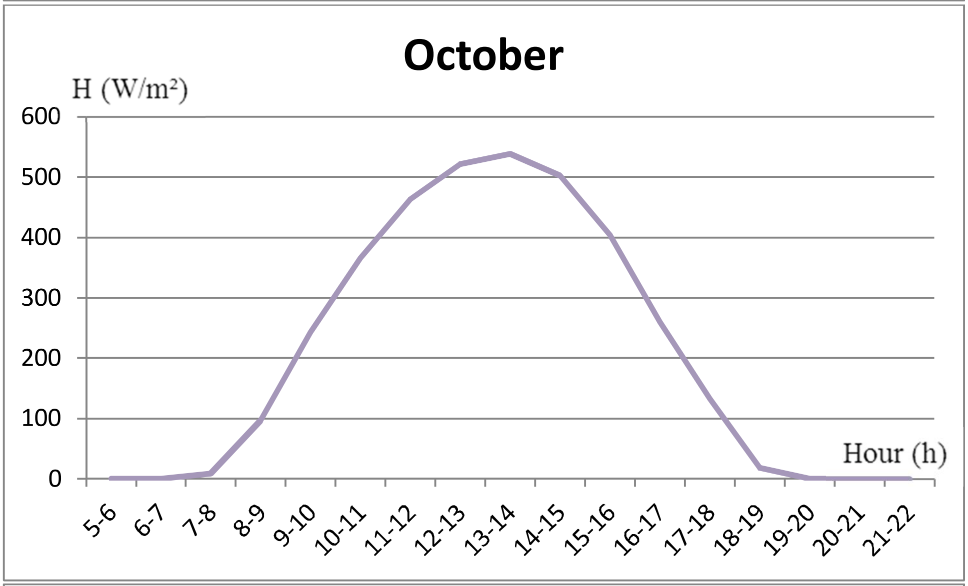
October
H (W/m²)
600
500
400
300
200
100
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
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14-15
15-16
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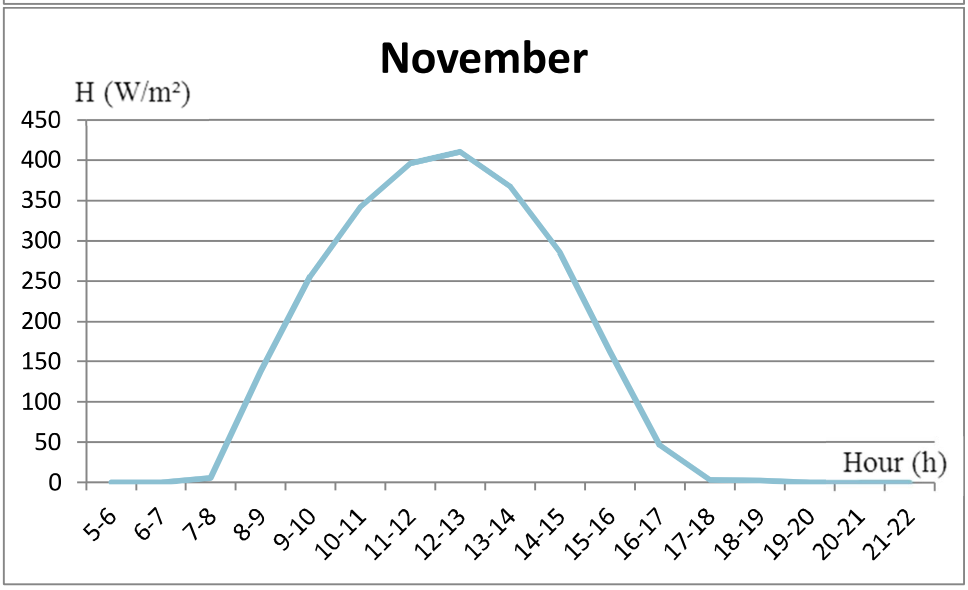
November
H (W/m²)
450
400
350
300
250
200
150
100
50
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
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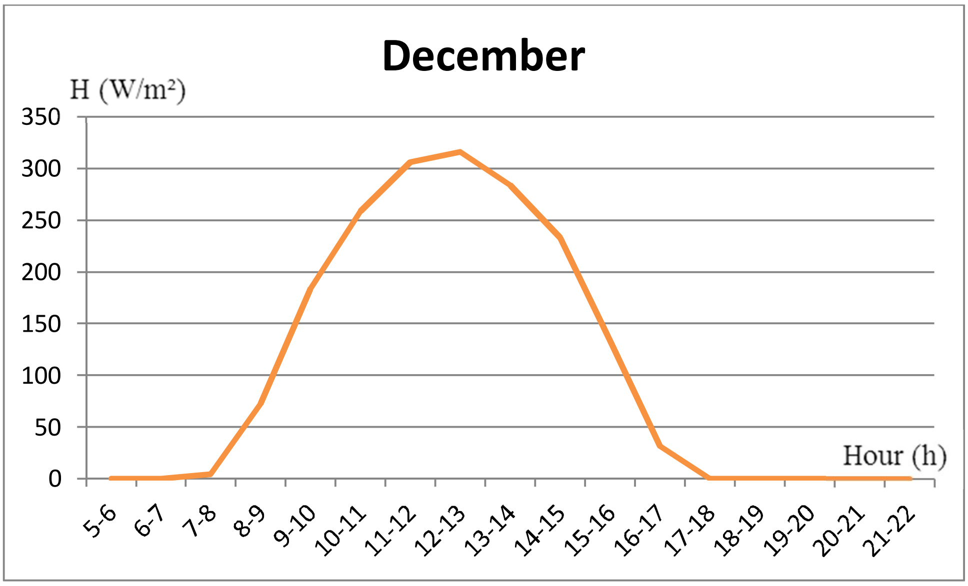

December
H (W/m²)
350
300
250
200
150
100
50
0
Hour (h)
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
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15-16
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