

Review

Empirical Models for the Estimation of Solar Sky-Diffuse Radiation. A Review and Experimental Analysis

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Abstract: Accurate solar radiation data are essential for the development of solar energy application systems. The limited availability of solar radiation data, and especially diffuse irradiance values, makes it vital to develop models to estimate these data. The development of estimation models has been the objective of many studies. This paper presents an extended review of the diffuse ratio (k) vs. clearness index (k_t) annual, monthly, daily, and hourly frequency regression models. It is however interesting to note that there is a dearth of such knowledge for diffuse ratio–clearness index regressions that are based on averaged data. Monthly-averaged daily global irradiation data are now easily available from the NASA website for any global location. Using existing models, it is possible to decompose the daily to averaged-hourly global irradiation values. The missing link so far has been hourly averaged diffuse irradiation. This article presents regression equations which could be used to estimate that information. For this purpose, hourly global and diffuse irradiation data was pooled from 19 different locations to obtain three latitude-dependent regression models relating the monthly-averaged hourly diffuse ratio (\bar{k}) to the clearness index (\bar{k}_t). The results show a high relationship between both variables. These regression equations could be used to estimate the averaged diffuse irradiation values from averaged global irradiation values, which are more easily available.

Keywords: solar radiation; diffuse ratio; clearness index; monthly-averaged hourly

1. Introduction

Alternative or renewable energy sources are able to provide the global current and future energy, with zero or almost zero greenhouse gas and pollutant emissions [1]. The sun is the most significant source of renewable energy available; it is not only naturally replenished, clean, and environmentally friendly, but it also drives the bases of the earth and causes nearly all the energy sources known today. Wind and hydro energy, biomass, and even fossil fuels are available because of the sun. Solar energy can generate heat and electricity for domestic and industrial use, and research in the field has increased significantly the efficiency and capacity of solar energy technologies. However, the potential of solar applications is much higher than the present use of this energy source.

The amount of energy generated from solar energy depends directly on the quantity of solar irradiance that is received in the earth and the efficiency of the devices used in the conversion process [2]. For a proper evolution of solar energy application systems, it is indispensable to have solar radiation data. Solar water heating, photovoltaic and solar-driven ventilation systems, daylighting and building

air conditioning are some solar energy applications where solar irradiance figures are required to obtain solar energy resource assessment. However, most of the meteorological stations only have records of global irradiation data measured on the horizontal plane. Weather stations rarely register direct and diffuse solar fractions [3].

The most demanded radiation data are mainly global and diffuse horizontal irradiation in hourly or sub-hourly frequency. However, it is not always possible to get long-term series for the previously mentioned parameters. Even though global irradiation at a monthly, daily, or hourly basis is the most commonly recorded parameter, it is only available in a limited number of meteorological stations. For example, there are 71 and 31 stations that measure these parameters in the UK and Spain, respectively.

It is much more expensive and relatively more complicated to measure the diffuse and direct components, and in consequence, these irradiation records are even scarcer than the global irradiation measurements [4]. In the UK for example, since 2002, the diffuse irradiation is measured in just two locations, at Lerwick (60.80° N) and Northern Camborne (55.21° N).

There are more meteorological stations that measure daily rather than hourly irradiation values, and it is more common to have daily global values rather than global and diffuse values. Almost all the radiometric stations are equipped with pyranometers to measure global solar irradiance, but only a few stations have equipment to measure the diffuse component of the solar tilted [5].

However, the contribution of the diffuse sky component in the irradiance received in the earth's surface is high enough to consider the diffuse irradiation an essential parameter for projects related to solar energy.

In South Africa, where much of the country is in the rather cloud-free anticyclonic belt of Southern Hemisphere, the diffuse irradiation contributes about the 30% of the annual short-wave energy received. In most of locations of this country, 523,000 and 581,111 Wh/m² are received indirectly over a year. This value is similar to 546,244 and 499,756 Wh/m² that Brussels and Berlin receive respectively during a year, where the ratio between diffuse and total irradiation is 0.55. In Antananarivo (Madagascar), the diffuse irradiation contributes the 40% (813,556 Wh/m²) of the annual total irradiation [6].

The diffuse irradiance is significant in many fields. One of those fields is the heat transfer application in buildings, where the irradiation is particularly important in tropical and sub-tropical climates where the energy contribution can reach very high levels. In the use of the solar energy, for example in the supply of hot water for domestic use, the diffuse irradiance can determine the continued efficiency of the process [6]. For house energy analysis, diffuse irradiance data are also required [7].

In those situations, it is essential to create correlation models to estimate diffuse irradiation data from the global irradiation records.

Therefore, numerous researchers have established empirical links to predict sky-diffuse irradiation based on available input variables, the clearness index (k_t) being one of the most important ones [4,8,9]. The clearness index relates the global and the extraterrestrial irradiation.

Liu and Jordan [10] were pioneers on the study of the correlation between diffuse ratio (k) and clearness index (k_t). Since then, several research teams have produced regression equations relating the previously mentioned parameters at an annual, monthly, daily, and hourly frequency for locations all over the world. Each regression equation is unique and statistically different.

The limited availability of solar radiation data records makes it essential to estimate irradiation values for sloped surfaces given values for horizontal surface. As mentioned before, the available radiation records are commonly for global irradiation on a horizontal surface. However, very few applications use the horizontal configuration; solar collectors for example are mounted tilted at some angle to it. Solar radiance data on tilted surfaces are essential prerequisites in several sciences. Agricultural meteorology, photobiology, animal husbandry, daylighting, and solar energy utilization, among others, require information about the available solar irradiance on slopes. The solar irradiance on a horizontal surface differs from the irradiance on a tilted surface [11].

Thus, this is an added reason for estimating diffuse irradiation values using correlation models [7], since both beam and diffuse irradiation components are used to estimate slope irradiance. It is not

possible to merely estimate the irradiation using trigonometric relationships, since the diffuse irradiance is not isotropic over the sky dome [12]. The irradiance that gets to the inclined collector does not only depend on its orientation but it is also affected by the assumed distribution that the diffuse irradiance has across the sky [7]. Once direct and diffuse irradiation values are estimated using correlation models, they can then be transported over tilted surfaces. This way, it is possible to estimate the completion of tilted flat plane collectors and other solar devices [13].

The estimation models' uncertainty and credibility will directly depend on the uncertainty of the available radiation data of any location. The more detailed the records are, the more accurate the predictions will be [11].

Considering the limited availability of the diffuse irradiation measurements and its importance in solar energy applications, the objectives of this article are:

1. To introduce an extended review of the existing regression models relating the diffuse ratio (k) and the clearness index (k_t) at an annual (Section 2), monthly (Section 3), daily (Section 4), and hourly (Section 5) frequency.
2. Monthly-averaged daily global radiation data are now easily available from NASA website for any global location. Using existing models, it is then possible to decompose the daily to averaged-hourly global irradiation. The missing link so far has been hourly averaged diffuse irradiation. This article intends to provide regression models to estimate the average-hourly diffuse irradiation using the freely accessible NASA website data.

2. Annual Average Diffuse Irradiation

Agricultural use of solar energy requires monthly or even annual irradiation data. The diffuse irradiation records are very scarce, and correlation models need to be established to estimate the diffuse component from the available parameters [14].

A great number of researchers have investigated the relationship between the annual k and the corresponding k_t . Muneer [11] developed the Equation (1) using data from several Indian meteorological stations (Gilat, Qrendi, Khormaskar, Tashkent, and Nice), which shows a strong correlation between both variables.

$$\frac{H_d \text{ annual}}{H_{\text{annual}}} = 1 - 1.04k_t \text{ annual} \quad (1)$$

Muneer and Hawas [15] analyzed data from 13 stations in India and showed that the annual global to extraterrestrial radiation fraction (k_t annual) varies between 0.53 and 0.61 in the tropics. The ratio of annual values of diffuse to extraterrestrial radiation (k_t annual) varies in a very narrow range, between 0.22 and 0.25 with an average value of 0.233. Stanhill [16] used three years of radiation values records in the south of Israel to develop a correlation between the annual diffuse to extraterrestrial ratio, and compared these relationships with those obtained in other locations to verify their applicability in the region. The ratio between the annual diffuse and extraterrestrial radiation reported by Stanhill for Gilat is 0.237. This value is also comparable to the results obtained for several UK locations, where the average value of the annual ratio was again 0.233 [11]. Other researchers, such as Mani and Chacko and Drummond, obtained diffuse to extraterrestrial values of 0.36 and 0.3, respectively [11].

According to Muneer it is easily possible to compute the annual-average extraterrestrial irradiation. Therefore, using a general value of 0.233 for the ratio between the annual diffuse to extraterrestrial radiation, it would be possible to obtain annual diffuse radiation data for any location [11].

3. Monthly Average Diffuse Irradiation

Specific solar radiation data at any location is needed, especially by solar engineers and architects [14]. The annual diffuse irradiation data are not enough for various solar energy applications, such as concentrating collectors, solar furnaces, etc. At least monthly diffuse irradiation data are needed for these applications. Therefore, for the locations where only the horizontal global irradiation is recorded, models to estimate diffuse irradiation are needed [17].

The monthly-average daily diffuse irradiation has been calculated considering the monthly average daily k_t as an independent variable (Equation (2)) [18].

$$k = \frac{H_d}{H} = g\left(\frac{H}{H_0}\right) = gk_t \quad (2)$$

Many experimental regression equations to estimate the monthly-averaged daily diffuse irradiation have been presented during the last decades [13]. The first correlation model between the monthly-averaged values of diffuse and global irradiation was defined by Liu and Jordan [10]. This model, together with the one brought by Page, are two of the most popular correlations [19]. From this pioneer research, a high number of regression models have been developed by fitting datasets from different places and frequencies [4]. Iqbal presented a correlation model between the k (H_d/H) and the fraction of the number of sunshine hours (S/S_0) [20]. Gopinathan, on the other hand, presented empirical models relating the k with the k_t , fraction of sunshine hours, and a combination of both [21].

Each of those models include experimental constants which are dependent on the time of year and the geographical location, therefore, most models are only valid for a specific place. According to El-Sebaai and Trabea, for example, a correlation between the k and k_t is adequate to calculate the month-to-month average daily diffuse irradiation in South Africa [7].

The table below (Table 1) shows some examples of the correlation models between k and k_t .

Table 1. Monthly-Average Diffuse Irradiation Models.

Author	Models
Liu and Jordan [10]	$k = 1.39 - 4.027k_t + 5.531k_t^2 - 3.108k_t^3$ (3)
Page [19]	$k = 1 - 1.13k_t$ (4)
Erbs et al. [22]	$k = 1.317 - 3.023k_t + 3.372k_t^2 - 1.769k_t^3$ (5)
Barbaro et al. [23]	$k = 1.0492 - 1.3246k_t$ (6)
	$k = 1.0896 - 1.4797k_t + 0.1471k_t^2$ (7)
	$k = 13.9375 - 76.276k_t + 144.3846k_t^2 - 92.148k_t^3$ (8)
Elhadidy and Abdel-Nabi [24]	$k = 1.039 - 1.741k_t^2$ (9)
	$k = -5.759 + 35.093k_t - 61.052k_t^2 + 33.115k_t^3$ (10)
Jain [25]	$k = -0.193 + 0.343k_t$ (11)
Tasdemiroglu and Sever [26]	$k = 1.6932 - 8.2262k_t + 25.5532k_t^2 - 37.807k_t^3 + 19.8178k_t^4$ (12)
Tiris et al. [27]	$k = 0.583 + 0.9985k_t - 5.24k_t^2 + 5.322k_t^3$ (13)
Kaygurus and Ayhan [28]	$k = 0.789 - 0.869k_t$ (14)
Tarhan and Sari [18]	$k = 0.9885 - 1.4276k_t + 0.5679k_t^2$ (15)
	$k = 1.027 - 1.6582k_t + 1.1018k_t^2 - 0.4019k_t^3$ (16)
Ibrahim [29]	$k = 0.86 - 0.86k_t$ (17)
	$k = 0.636 - 0.279k_t - 0.194k_t^2 - 0.383k_t^3$ (18)
Klein [30]	$k = 1.390 - 4.027k_t + 5.531k_t^2 - 3.108k_t^3$ (19)
Iqbal [20]	$k = 0.958 - 0.982k_t$ (20)
	$k = 0.914 - 0.847k_t$ (21)
Bortolini et al. [3]	$k = 0.9888 + 0.3950k_t - 3.7003k_t^2 + 2.2905k_t^3$ (22)
Trabea [31]	$k = 0.534 + 0.384k_t - 1.036k_t^2$ (23)
Aras et al. [32]	$k = 1.0212 - 1.1672k_t$ (24)
	$k = 1.1244 - 1.5582k_t + 0.3635k_t^2$ (25)
Ulgen and Hepbasli [17]	$k = 0.6772 - 0.4841k_t$ (26)
	$k = 0.981 - 1.9028k_t + 1.9319k_t^2 - 0.6809k_t^3$ (27)
Aras et al. [32]	$k = 1.7111 - 4.9062k_t + 6.6711k_t^2 - 3.9235k_t^3$ (28)

4. Daily Average Diffuse Irradiation

In many solar applications, monthly average diffuse irradiation data are not enough. Daily or even hour-by-hour solar irradiation data represent an important requirement. The first regression equation, which relates the daily k and the daily k_t , was also developed by Liu and Jordan [10]. This correlation did not consider the shade ring of the k_t , and they used just one value of the extraterrestrial irradiation for the middle days of the month.

Choudhary developed a model for New Delhi using only three months of data and obtained higher k values than the Liu and Jordan model [33]. At first, they associated this to the high dust content in New Delhi and the small sample of data. However, as it was proven later, these higher k values are due to the lack of compensation of the shade ring of shadow band in the Liu and Jordan study [11].

Many researchers re-investigated the regression equation presented by Liu and Jordan for different locations in the world and defined new models using daily-integrated data of global and diffuse solar irradiance values. All the investigators calculated the extraterrestrial irradiation for each day. In order to estimate the daily extraterrestrial irradiation, it is possible to use the following equation (Equation (29)) [11].

$$H_0 = \left(\frac{0.024}{\pi}\right) I_{SC} \left[1 + 0.033 \cos\left(\frac{360DS_0}{365}\right)\right] \left[\cos\varphi \cos\delta \sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right) \sin\varphi \sin\delta\right] \quad (29)$$

Collares-Pereira and Rabl used 1-4 years data for five stations in the USA measured with a pyrheliometer. They confirmed Liu and Jordan's model's validity and concluded that the numerical inaccuracies of the original work were due to the use of uncorrected values of diffuse irradiation in the regression, use of a just one value of extraterrestrial insolation during each month, and not taking into account seasonal variations in the diffuse to hemispherical ratio [34]. Even though they found a seasonal trend in the data, they used all data as a group [11]. Table 2 sums up the models correlation daily values of the diffuse irradiation.

Table 2. Daily Average Diffuse Irradiation Models.

Author	Models	
Collares-Pereira and Rabl [34]	$k = 0.99$ for $k_t < 0.17$ $k = 1.188 - 2.272k_t + 9.473k_t^2 - 21.856k_t^3 + 14.648k_t^4$ for $0.17 < k_t \leq 0.8$	(30)
Erbs et al. [22]	$k = 1 - 0.2727K_t + 2.4495k_t^2 - 11.9514k_t^3 + 9.3879k_t^4$ for $k_t < 0.715S_0 = \frac{2}{15}\omega_s$ $k = 0.143$ for $k_t \geq 0.715$	(31)
	$k = 1 + 0.28332k_t - 2.5557k_t^2 + 0.8448k_t^3$ for $k_t < 0.722$ $k = 0.175$ for $k_t \geq 0.722$	(32)
Rao et al. [35]	$k = 0.9493 + 1.1314k_t - 5.7688k_t^2 + 4.5503k_t^3 - 1.2457k_t^4$	(33)
Muneer and Hawas [15]	$k = 0.98$ for $k_t < 0.2$ $k = 1.024 + 0.47k_t - 3.622k_t^2 + 2k_t^3$ for $0.2 \leq k_t \leq 0.77$ $k = 0.16$ for $k_t > 0.77$	(34)
Tuller [36]	$k = 1.20 - 1.20k_t$	(35)
Saluja and Muneer [37]	$k = 0.98$ for $k_t < 0.2$ $k = 0.962 + 0.779k_t - 4.375k_t^2 + 2.716k_t^3$ for $k_t \geq 0.2$	(36)

Erbs et al. [22] presented two seasonal regression equations, one for winter and another one for the rest of the year. The research was made using mean values of the k over finite intervals of the k_t [11], and obtained an equation for each of the seasonal correlations. The equations from the summer data and spring and autumn data were almost equal.

Rao et al. used individual values of k regressed against k_t to develop a seasonal as well as an annual regression equation. They developed simple linear regression models and more than 85% in the variability of the fraction between diffuse and global irradiation was explained by the models [35].

Muneer and Hawas [15] used three years of measurements from 13 Indian stations, all of them between 8.5° N and 28.5° N latitude, to develop regression equations for each individual station as well as for the whole country of India. The regression obtained from the equations (Equation (34)) concluded a high relationship between the k and k_t for individual locations ($R^2 = 0.893\text{--}0.95$) and also for the whole country of India ($R^2 = 0.89$).

Tuller [36] presented a model using one year of daily data from four Canadian stations. They not only found a latitude effect in the results, but also studied the impact the reflectivity of the surface has on the diffuse irradiation, concluding that it only affected in the 27% of the variation for the diffuse transmission coefficient [11].

Saluja and Muneer [37] studied three years of data from five locations in the UK (Easthampstead, Aberporth, Aldergrove, Eskdalemuir, and Lerwick) and presented a single regression equation for each station and a single correlation model for the five locations.

5. Instantaneous Hourly Diffuse Irradiation

Monthly irradiation data and even daily irradiation data are not enough for many solar engineering applications systems. For those applications, at least hourly irradiation values are needed. Liu and Jordan [10] were the first researchers investigating the correlation between the diffuse and global radiation on a parallel to the ground surface; however, their original regression model was conceived for daily values instead of hourly values.

Since then, several researchers have developed hourly correlation equations relating the k and the k_t .

Orgill and Hollands, using four years of data from Toronto (Canada), presented a linear model to estimate k with the hourly k_t . They used a shadow-band pyranometer to measure the diffuse irradiance [38].

Erbs et al., following the work of Orgill and Hollands, developed a regression equation using four locations in the 31–42° N latitude range. They used pyroheliometric data, where the diffuse irradiance was calculated deducing the direct irradiance from the global irradiance, which was recorded with a pyranometer [22].

Reindl et al. developed correlations used data from five locations from Europe and North America in order to minimize the standard error of the models similar to the one presented by Liu and Jordan, analyzing the effect of the most frequently recorded climatic parameters on the diffuse fraction [39].

Hawladar derived the second-order polynomial regression with measurements from a tropical place in Singapur. They suggested an equation to calculate k of the hourly, daily and monthly global insulations on a horizontal surface [40]. The hourly regressions trend was similar to the equations developed by Orgill and Hollands [38] and Spenser [41], supporting the latitude dependence that they claimed.

Chandrasekaran and Kumar developed a fourth-order polynomial regression equation using measurements from a tropical site in Madras (India) [42]. This correlation was compared, using the standard and relative standard deviation, to the ones defined by Orgill and Hollands, Erbs et al. and Reindl et al., which were developed using data from warm locations [22,38,39]. It was shown that the new regression equations are more accurate and the best results were found when the seasonal effect was considered. It was also found that the hour-by-hour k is higher in tropical sites than in warm areas, with a much higher k in the rain season when the hourly k_t is higher.

Boland et al. used 15-min data from a meteorological station in Victoria to determine if the smoothing caused with the use of hour-by-hour data has an effect in overall results. They found that it is possible to use the same model for 15-min and hourly data [7].

Miguel et al. developed a third order polynomial regression equation for hourly k values using data from several countries in North Mediterranean locations [43].

Oliveira et al. developed a fourth-order polynomial regression equation with data from a tropical location in Sao Paulo, and determined that the general characteristics of the k regression curves and their seasonal alterations are similar to the ones found by other researchers with similar latitude for hourly, daily, and monthly values [44].

Karatasou et al. presented a third-order polynomial correlations with the objective of reducing the standard error of the regression equations similar to the one developed by Liu and Jordan. The research was based on measurements from Athens, Greece [45]. Using the same records from Athens, Soares et al. presented a fourth-order polynomial equation, including the atmospheric long-wave radiation as an input. It was found that these data improves the neural-network performance [46].

The table below (Table 3) shows a review of the mentioned hourly correlation equation of different researchers. All the models relate the k with k_t .

Table 3. Instantaneous Hourly Irradiation Models.

Author	Models	
Orgill and Hollands [38]	$k = 1 - 0.249k_t$ for $k_t < 0.35$ $k = 1.157 - 1.84k_t$ for $0.35 \leq k_t \leq 0.35$ $k = 0.177$ for $k_t < 0.75$	(38)
Erbs et al. [22]	$k = 1 - 0.099k_t$ for $k_t < 0.22$ $k = 0.9511 - 0.160k_t + 4.388k_t^2 - 16.638k_t^3 + 12.336k_t^4$ for $0.22 \leq k_t \leq 0.80$ $k = 0.165$ for $k_t < 0.80$	(39)
Reindl et al. [39]	$k = 1.02 - 0.249k_t$ for $k_t < 0.3$ $k = 1.45 - 1.67k_t$ for $0.3 < k_t < 0.78$ $k = 0.147k_t$ for $k_t \geq 0.78$	(40)
Hawladar [40]	$k = 0.915k_t$ for $k_t \leq 0.225$ $k = 1.135 - 0.9422k_t - 0.3878k_t^2$ for $0.225 < k_t < 0.775$ $k = 0.215k_t$ for $k_t \geq 0.775$	(41)
Spencer [41]	$k = a_3 - b_3k_t - 0.3878k_t^2$ for $0.35 < k_t < 0.75$	(42)
Chandrasekaran and Kumar [42]	$k = 1.0086 - 0.178k_t$ for $k_t \leq 0.24$ $k = 0.9686 - 0.13250k_t - 1.4183k_t^2 + 10.1862k_t^3 + 8.3733k_t^4$ for $0.4 < k_t < 0.80$ $k = 0.197$ for $k_t > 0.80$.	(43)
Boland et al. [47]	$k = 1/[1 + \exp(-5.0033 + 8.6025k_t)]$	(44)
Miguel et al. [43]	$k = 0.995 - 0.081k_t$ for $k_t \leq 0.21$ $k = 0.724 + 2.738k_t - 8.32k_t^2 + 4.967k_t^3$ for $0.21 < k_t < 0.76$ $k = 0.18$ for $k_t > 0.76$	(45)
Oliveira et al. [44]	$k = 1$ for $k_t \leq 0.17$ $k = 0.97 + 0.8k_t - 3k_t^2 - 3.1k_t^3 + 5.2k_t^4$ for $0.17 < k_t < 0.75$ $k = 0.17$ for $k_t > 0.75$	(46)
Karatasou et al. [45]	$k = 0.9995 - 0.05k_t - 2.4156k_t^2 + 1.4926k_t^3$ for $0 < k_t \leq 0.78$ $k = 0.20$ for $k_t > 0.78$	(47)
Soares et al. [46]	$k = 1.0$ for $k_t \leq 0.17$ $k = 0.90 + 1.1k_t - 4.5k_t^2 + 0.01k_t^3 + 3.14k_t^4$ for $0.17 < k_t < 0.75$ $k = 0.17$ for $k_t > 0.75$	(48)

For the estimation of the hourly k_t values, it is necessary to estimate the hourly extraterrestrial irradiation values. The following equation can be used for that purpose.

$$H_0 = I_{sc}[1 + 0.0172024DS_0] \sin \alpha \quad (37)$$

It is important to mention that the long-wave radiation, which provides regional scale cloud-cover information, is more important than more common meteorological variables, such as air temperature and atmospheric pressure.

6. Artificial Neural Networks (ANN)

Artificial intelligence is a promising method to model solar radiation and a few models based on artificial neural network (ANN) have been developed to estimate radiation in different regions of the world. An adaptive neuro-fuzzy approach was defined by Olatomiwa et al. using air temperature and sunshine duration to predict solar radiation in Nigeria [48]. The same researchers also developed a support vector machines firefly algorithm, ANN, and genetic programming models to estimate solar radiation in the Iranian city [49]. Park et al. used a topographic factor and sunshine duration to estimate the spatial distribution of solar irradiance in South Korea [50]. A Markov transitions matrix method was proposed by Aguiar et al. to estimate daily irradiation values k_t [51]. A Gaussian model for generating synthetic hourly irradiation was also presented by Aguiar and Collares-Pereira [52]. Amrouche and Pivert used combine spatial modeling and ANN techniques to predict global irradiation in two French locations [53]. Linares-Rodriguez et al. used ANN methods to estimate solar radiation based on latitude, longitude, day of the year, and other climatic parameters in Spain [54].

Furthermore, satellite images are also used to study the solar radiation spatial-temporal variations around the world. Hay was a pioneer in introducing the modeling methods for satellite-based estimates of solar radiation at the Earth's surface [55]. Cano et al. developed a method to estimate the global irradiation from meteorological satellite data [56]. Antonanzas-Torres et al. compared the global solar irradiation values from a satellite estimate model and on-ground measurement in Spain [57].

However, most of the presented models to estimate solar radiation are based on parameters that are more readily available. Some of these parameters are extraterrestrial irradiation, mean temperature, maximum temperature, soil temperature, relative humidity, number of rainy days, altitude, latitude, total precipitation, cloudiness, and evaporation, among others [58].

7. Monthly Average Hourly Diffuse Irradiation: Experimental Analysis

In the NASA website (<http://eosweb.larc.nasa.gov>) it is currently available information to get daily-averaged irradiation data for most of the worldwide locations. This information includes long-term estimated values of meteorological measures and surface solar energy fluxes provided by satellite systems. These data meet the needs of renewable energy community and it has been proven they are accurate enough to provide consistent solar and meteorological data for locations where records are scarce or non-existent [59].

The information that is provided in the NASA website, which is available in the public domain, can be used to construct a computational chain to get all means of solar energy estimations that need hour-by-hour horizontal and slope, global, and diffuse irradiation data.

7.1. Step 1. Monthly-Averaged Hourly Global Irradiation

The first step to estimate all manners of solar energy data is to decompose the freely obtainable monthly-averaged daily irradiation data from the NASA website into monthly-averaged hour-by-hour global irradiation values (Figure 1).

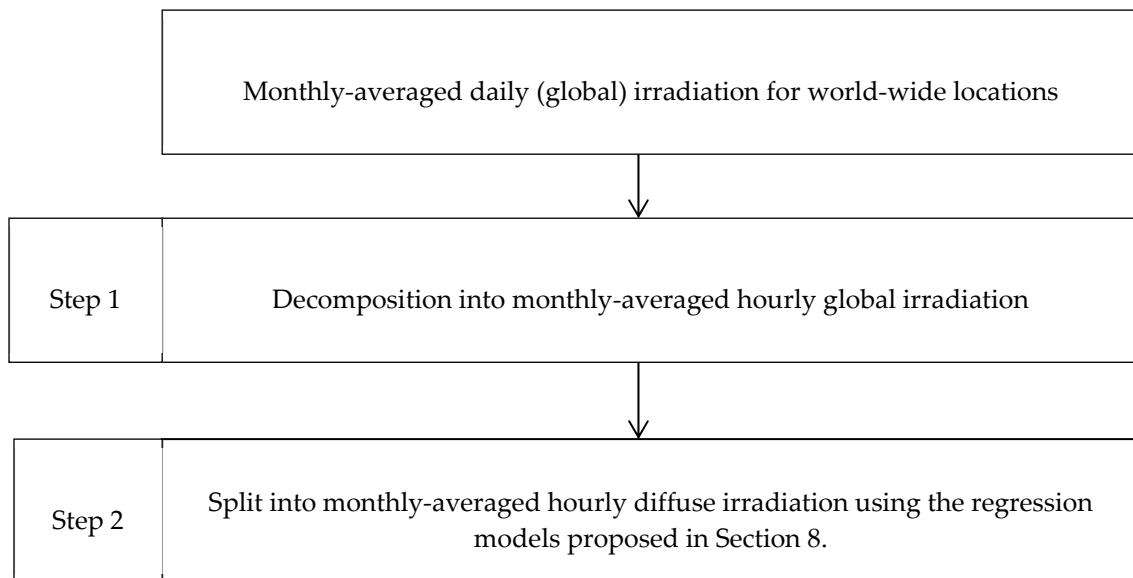


Figure 1. Computational chain to get all manner of solar energy estimations [59–61]. Source: <http://eosweb.larc.nasa.gov>.

Hourly irradiation data requires a very accurate modelling of solar processes. Therefore, the hourly average irradiation is the nearest approach to the real average radiation, which is obtainable from the commonly available solar radiation data [11].

Daily solar irradiation records are more accessible since more locations have the technology to measure it. It is logical to consider that there exists a correlation between daily and hourly solar irradiation.

Whillier was a pioneer in this field. They plotted experimental ratios between daily to hourly global solar irradiation data derived from widely separated locations against the sunset hour angle [62].

A mean curve was obtained for every hour, and it was proved that the deviation of any single point from the mean curve was not higher than $\pm 5\%$ for the hours between 9 am and 3 pm sun time.

Meteorological stations usually publish monthly-averaged values of daily global irradiation. However, when this information is not available, it could be obtained from solar models which use the long-term sunshine data [11].

Liu and Jordan developed a set of correlation curves extending Willier's work, which shows the effect of the day length and the shift of the hour from solar noon on the ration between the hourly to daily irradiation [10]. These regression curves enable the calculation of the averaged-hourly irradiation data when daily irradiation records are available.

7.2. Step 2. Experimental Analysis

For the experimental analysis of this study, nineteen worldwide locations were chosen, with available hour-by-hour global and diffuse irradiation values in the period (1990 to 2002) found in the respective meteorological office for each location. The table below (Table 4) shows the latitude and longitude and period of observation of each location.

Table 4. Nineteen Worldwide Locations for the Study.

Country	Location	Latitude	Longitude	Period of Observation
India	Chennai	13.08	80.18	1990–1994
	Pune	18.32	73.85	1990–1994
Kingdom of Bahrain	Bahrain	26.03	50.61	2000–2002
State of Kuwait	Kuwait	29.22	47.98	1996–2000
Spain	Almeria	36.83	−2.38	1993–1998
Portugal	Faro	37.02	−7.96	1982–1986
	Lisbon	38.71	−9.15	1982–1990
Spain	Madrid	40.40	−3.55	1999–2001
	Girona	41.97	2.76	1995–2001
United Kingdom	Camborne	50.21	5.30	1981–1995
	Crawley	51.11	0.19	1980–1992
	Bracknell	51.42	0.75	1992–1994
	London WCB	51.52	0.11	1975–1995
	Aberporth	52.13	4.55	1975–1995
	Hemsby	52.70	1.69	1981–1995
	Finningley	53.48	0.98	1982–1995
	Aughton	53.54	2.91	1981–1995
	Aldergrove	54.65	−6.24	1968–1995
	Stornoway	58.22	6.39	1982–1995

Monthly-averaged hourly values were estimated for the global and diffuse irradiation using the information of each location for the given period of time. A visual basic code was then defined for this purpose. The monthly average hourly diffuse ratio (\bar{k}) and the clearness index (\bar{k}_t) were calculated for each location. In order to avoid erroneously recorded data, the conditions below (Equations (49) and (50)) were used. Extraterrestrial irradiation cannot be greater than global irradiation and diffuse irradiation cannot be greater than global irradiation.

$$k_t = \frac{H}{H_0} \rightarrow H < H_0 \quad (49)$$

$$k = \frac{H_D}{H} \rightarrow H_D < H \quad (50)$$

Radiance, expressed as W/m^2 is the emanating power from a radiating source, on the other hand irradiance is the receipt of radiated power at the receiving surface. Radiation and irradiation, likewise are energy quantities that are expressed as Wh/m^2 or kWh/m^2 . The latter is the integration of power over a given interval of time, so one may have the power integrated over a five-minute or an hour time interval. The UK meteorological office has one of the oldest solar radiation recording networks in the world and their radiation records are available as hourly-integrated values expressed as Wh/m^2 [11].

The monthly-averaged k_t of the 19 locations was regressed against the monthly-averaged k . The following figures (Figures 2–4) show the corresponding scatter plot.

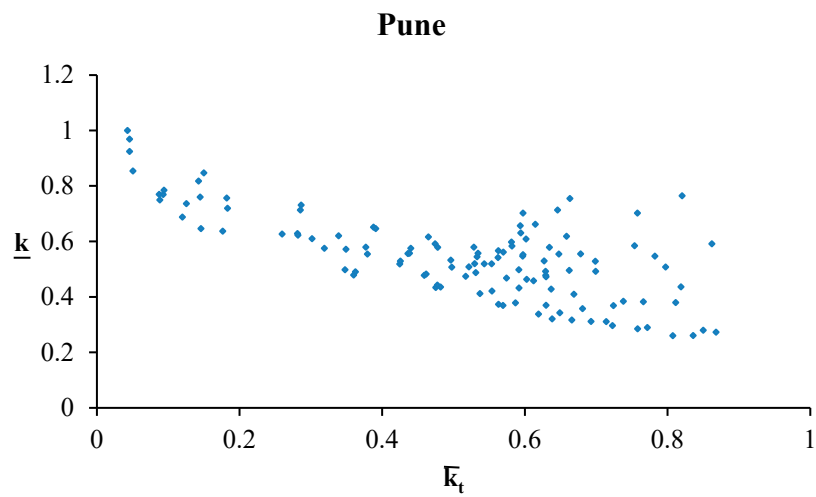


Figure 2. Monthly-averaged hourly k_t vs. k for Pune.

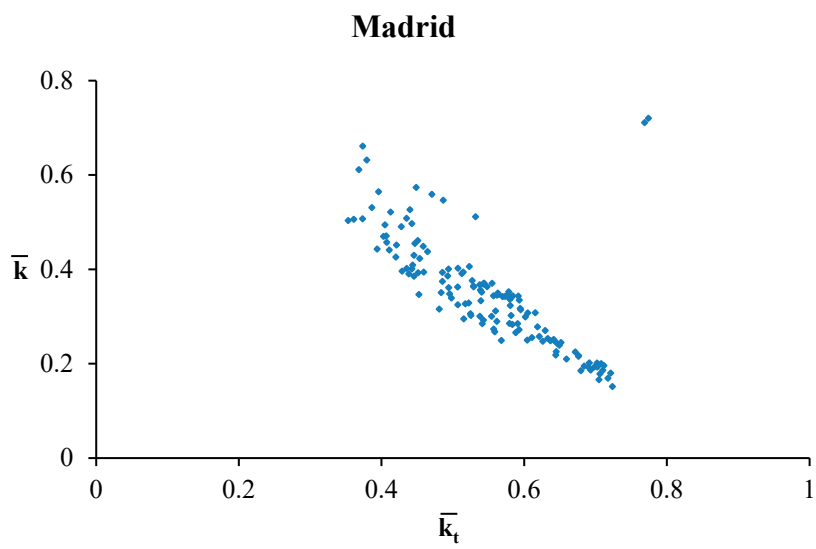


Figure 3. Monthly-averaged hourly k_t vs. k for Madrid.

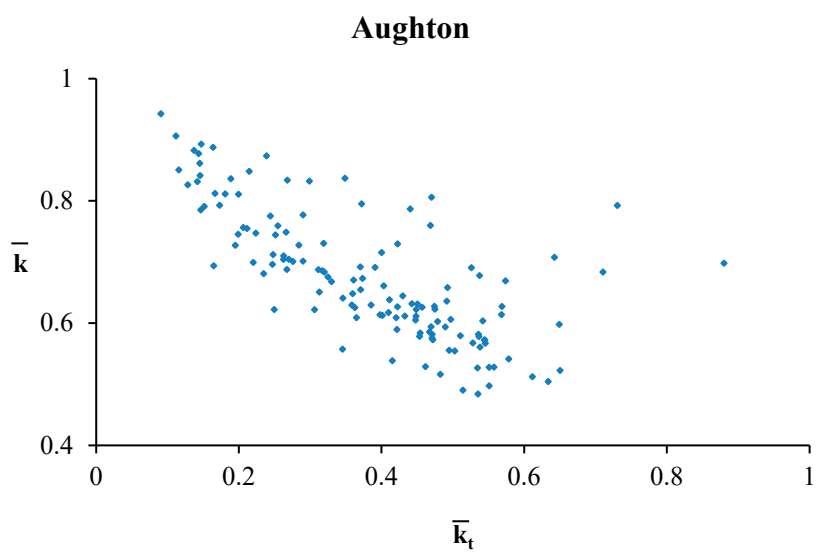


Figure 4. Monthly-averaged hourly k_t vs. k for Aughton.

In addition, for a 0.05 width increment of the bandwidth of the k_t , the respective values of averaged k were obtained. The table below (Table 5) shows the average k and the average k_t in the columns one and two, respectively. The third column presents the number of points considered to calculate the average values. The values in italics correspond to average values calculated only with one or two points. These average values have not been taken into account, since there is not enough information to assure those data are reliable.

Table 5. Averaged k Values for Each Increment at Bandwidth of k_t of 0.05 Widths.

PUNE			MADRID			AUGHTON		
0.083	0.786	5	0.376	0.551	9	0.136	0.856	10
0.138	0.749	6	0.429	0.457	21	0.178	0.791	10
0.180	0.705	3	0.475	0.405	18	0.231	0.742	11
0.279	0.665	5	0.528	0.354	25	0.272	0.741	13
0.331	0.575	5	0.575	0.317	29	0.325	0.676	11
0.376	0.567	6	0.628	0.259	17	0.372	0.661	12
0.433	0.548	5	0.679	0.206	11	0.424	0.638	17
0.476	0.51	10	0.711	0.182	10	0.473	0.612	21
0.531	0.512	9	0.771	0.716	2	0.532	0.574	15
0.579	0.522	18				0.564	0.572	7
0.628	0.488	16				0.634	0.581	4
0.677	0.484	10						
0.725	0.34	4						
0.707	0.471	7						
0.824	0.397	6						

The following figures (Figures 5–7) show the averaged k and k_t plots for each location.

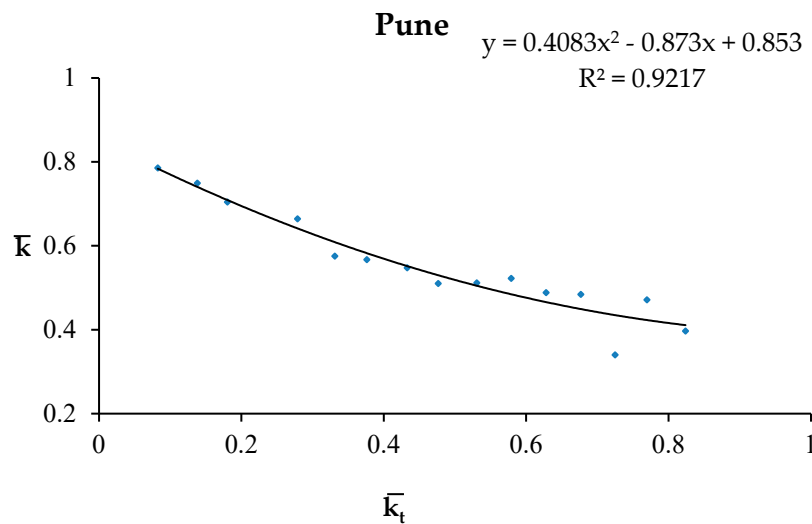


Figure 5. Average values of k vs. k_t for Pune.

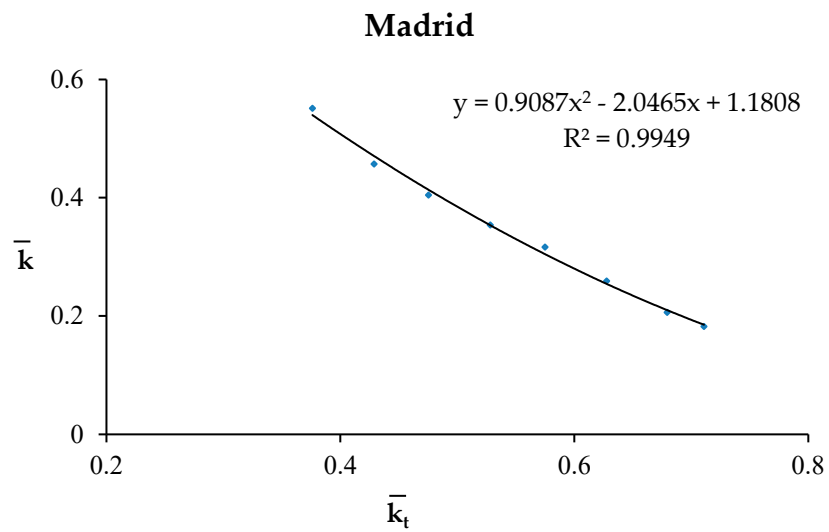


Figure 6. Average values of k vs. k_t for Madrid.

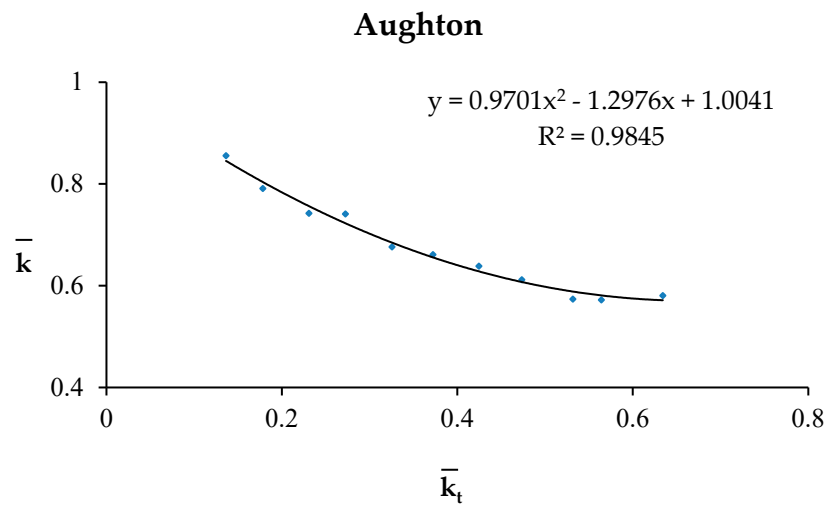


Figure 7. Average values of k vs. k_t for Aughton.

The same process was repeated with all the locations. Figure 8 shows the regression of the average values of k and k_t of the 19 worldwide locations together.

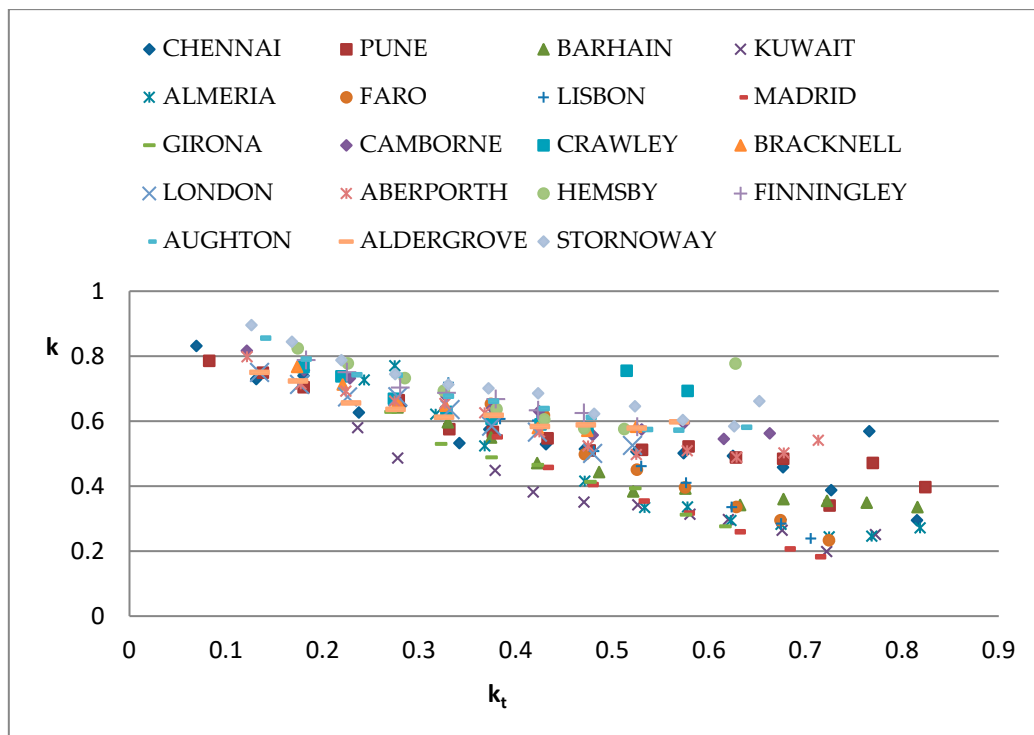


Figure 8. Regression of averaged values of k_t vs. k for the 19 locations.

Even though it is not possible to obtain a unique regression equation for the 19 locations, due to the high dispersion of the results, the graph clearly indicates the existence of different sub-models. Therefore, the data have been settled in an increasing order of latitude. Figures 9–11, respectively show the regression curves for the locations in a narrower range of latitude.

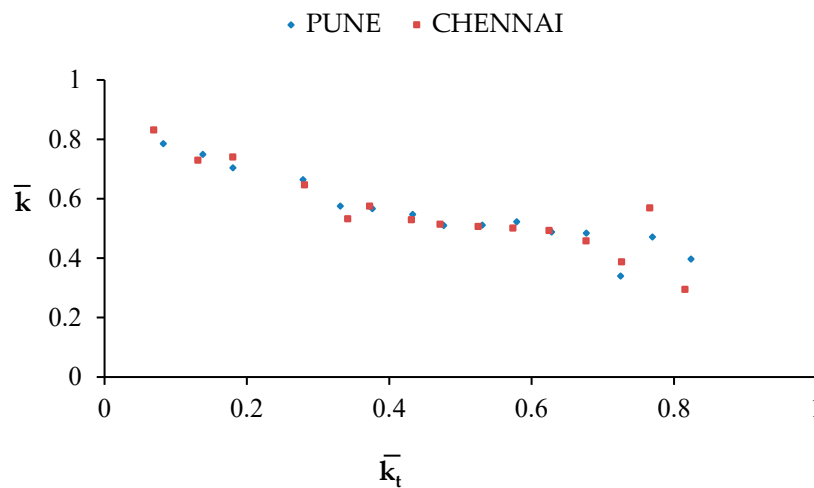


Figure 9. Average values of the k for cities in the 13°–20° N.

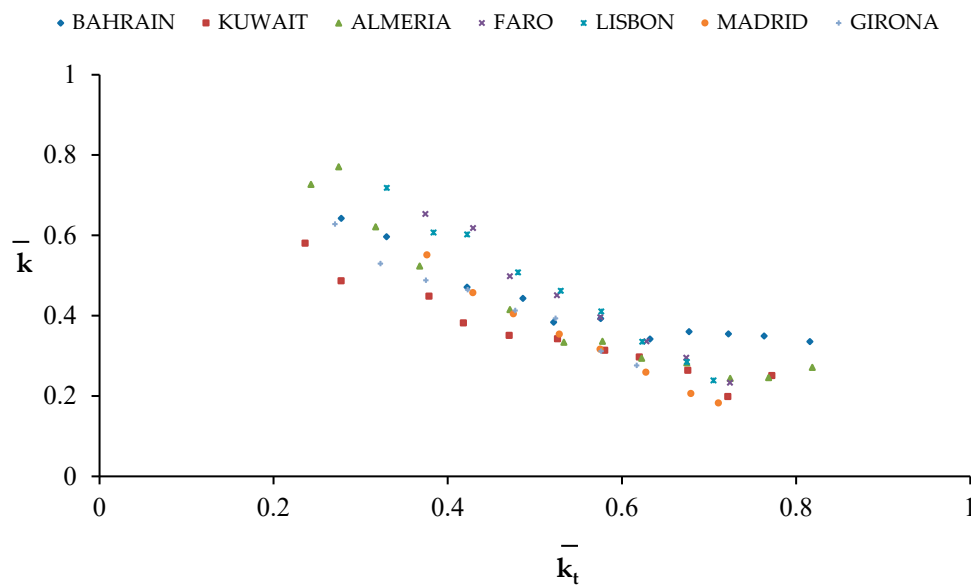


Figure 10. Average values of the k for cities in the 20°–42° N.

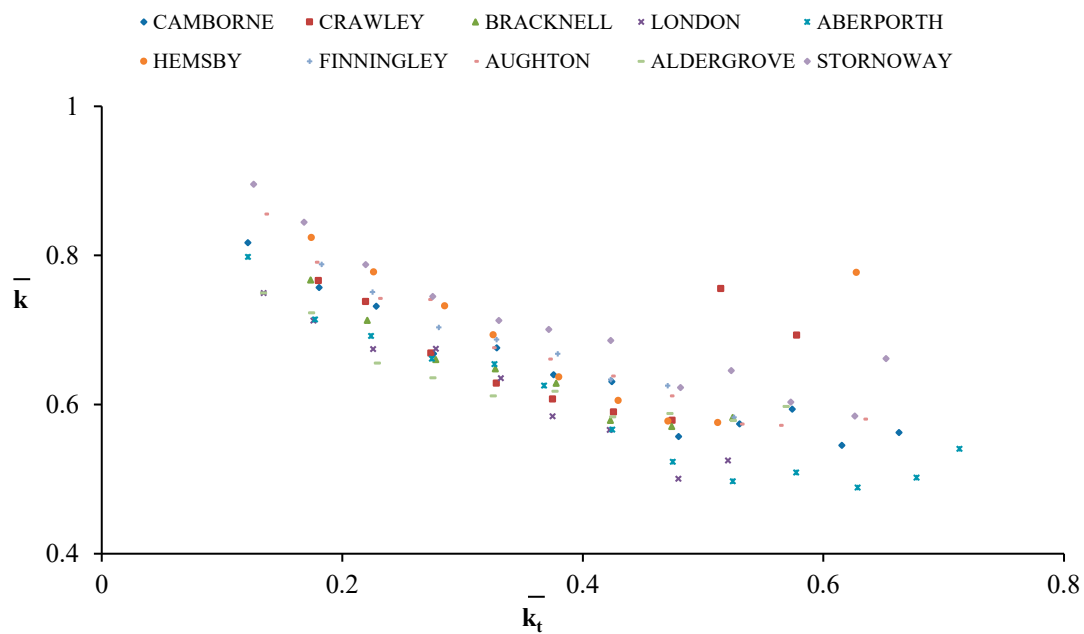


Figure 11. Average values of the k for cities in the 50°–58° N.

The three figures (Figures 9–11) show the potential for a single regression model for each latitude group.

There is an increasing tendency of k in the top end of k_t . This fact is especially notorious in the data from the 10 locations of the highest latitude group that are under examination, as can be seen in Figure 10. This phenomenon is related with simultaneous existence of two astronomical/weather-related situations. A more extended explanation of this phenomenon is developed in Muneer et al. [50].

The Figure 12 shows the definitive regression curves for the three latitude ranges.

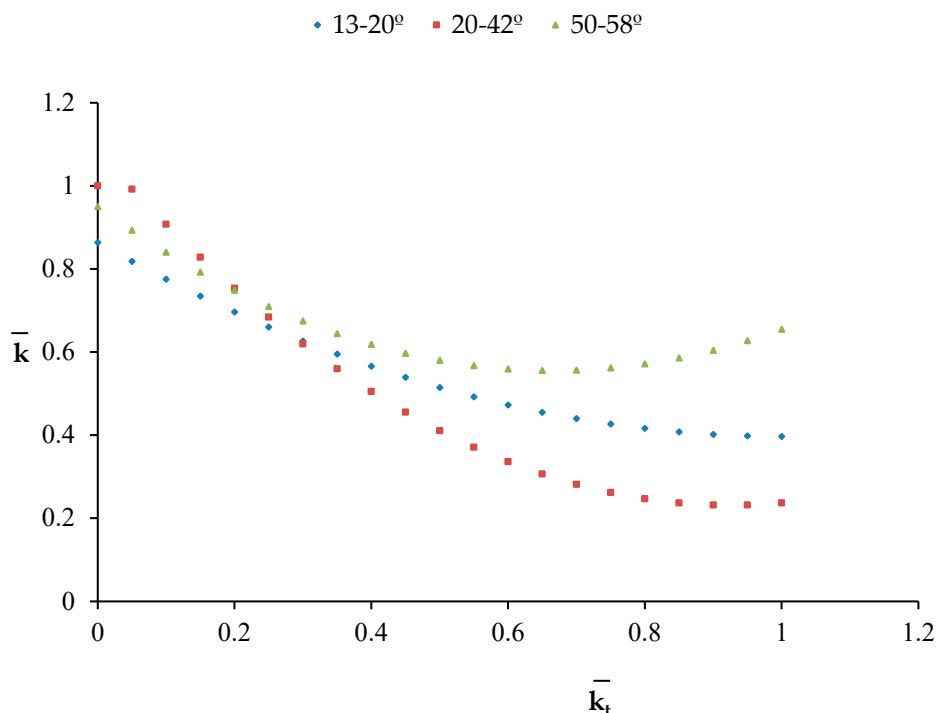


Figure 12. Regression curves and equations.

The definitive regression equations to estimate monthly-averaged hourly diffuse irradiation values for the latitude ranges developed are shown in the Table 6 below:

Table 6. Monthly-Averaged Hourly Diffuse Irradiation Equations.

LATITUDE	EQUATION	R ²	R
13–20° N	$k = 0.4623k_t^2 - 0.9291k_t + 0.8636$	0.87	0.93 (51)
20–42° N	$k = 0.994k_t^2 - 1.8386k_t + 1.0815$	0.80	0.89 (52)
50–58° N	$k = 0.8896k_t^2 - 1.185k_t + 0.9502$	0.80	0.89 (53)

There are three main points worth mentioning in this study. First, it is not possible to obtain a unique regression equation for the nineteen worldwide locations. However, a high correlation is observed between the average k and k_t , with high values of the corresponding coefficient of determination (R^2) and coefficient of correlation (R) for narrower range of latitude. It is also important to note that the shape in the three regression models is concave, instead of convex, as in the hour-by-hour regression equations.

The adequacy of these correlation models has been proven in this study, thus, the Equations (51)–(53) can be used to estimate diffuse irradiation values in sites located in these latitude ranges.

8. Conclusions

The determination of the solar diffuse irradiation is essential for solar water heating, photovoltaic and solar-driven ventilation systems, daylighting and building air conditioning applications, among others. The prediction of these data provides a notorious reduction in energy consumption, since they help to estimate real radiation values and reduce the uncertainty. A large number of researchers have focused on the development of regression models to calculate the missing radiation data for several locations in the world. This research presents an extended review of those correlation models in annual, monthly, daily, and hourly frequencies, using the k_t as a variable.

For the past 40 years, numerous researchers have presented such regressions, especially for hour-by-hour irradiation data, for different areas of the world. It is important to note that there is not available information in the literature for k vs. k_t correlations based on averaged data.

The present study has analyzed the relationship between averaged-hourly diffuse and global irradiation using k vs. k_t regression models for 19 world locations. The results show that it is possible to get regression equations to complete the above-mentioned missing link. The study concludes that there is a high correlation between both variables, even though it is not possible to obtain a unique regressed curve for all the locations in the latitude group under study. Latitude dependent regression curves have been obtained, which are noticeably different from previously available hour-by-hour correlations. The shape of the curves is concave instead of convex as in the hour-by-hour regression models reported by other researchers.

There is no reason to doubt the possibility of developing regression equations for other data records that are available for other locations in the world. The present work has the potential to extend the application to locations in latitudes not included in this study and to add more locations to each latitude group in order to gain accuracy in the results.

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Nomenclature

H : Annual, monthly and daily global horizontal solar irradiation (Wh/m²)

H_0 : Extraterrestrial irradiation on a horizontal surface (Wh/m²)

H_d : Diffuse irradiation (Wh/m²)

H_b : Beam irradiation (Wh/m²)

$k_t = H/H_0$: Clearness index

$k = H_d/H$: Diffuse ratio

S_0 : Length of the day (h)

S : Daily hours of bright sunshine (h)

I_{SC} : Solar constant 1.367W/m²

D : Number of days of the year starting from first January

φ : Latitude of the site (°)

δ : Solar declination (°)

ω_s : Sunset hour angle (°)

α : Solar altitude (°)

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