Review of Solar Radiation estimation and Solar Data Banks elaboration methodologies over Greece

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Abstract: - The wide spectrum of solar energy applications has been thrived in the last years all over the world. The design of such applications requires the knowledge of solar radiation in any time base (monthly, daily and/or hourly). This requirement can be satisfied by the elaboration of detailed solar radiation data banks, where meteorological stations network are installed, or, where no such data are available, by using various methodologies for the estimation of this quantity. For both cases many methodologies have been proposed and validated all over the world by many scientists. Greece, because of its geographical position, has a significant solar potential that can be exploited for the development of various solar energy applications. This paper is an attempt to review, namely to gather and present some of the models for global solar radiation estimation along with data bank elaboration methodologies that have been adapted in Greek climatic conditions.

Key-Words: - solar energy, solar radiation, renewable energy, clean environment, greenhouse effect, meteorological data banks.

1 Introduction

According to Kyoto Protocol European Union should reduce CO_2 emissions by 8% until year 2010, with reference level the emissions of the year 1990. European Union's Directive 2001/77/EC on renewable energy indicative target for Greece is 20.1% coverage of the country's total electricity demand by renewable energy systems until 2010 [1]. Electricity generation in Greece from renewable energy systems was 4.145 GWh in 2000 with a total installed capacity of 3.334 MW. This corresponds to 5% of the Greek total primary energy supply. It is obvious that Greece has to take drastic steps towards the target of 20.1% coverage of total electricity demand by renewable energy systems, until 2010.
Solar energy is a renewable, clean and healthy source of energy and its extended application can help Greece and European Union reach their indicative targets. Solar energy feasibility studies and applications require detailed "knowledge" of solar insolation on monthly, daily and/or hourly basis. This "knowledge" may be obtained, either by the elaboration of data banks, in which recorded data are available, or by the use of solar radiation prediction methodologies and techniques, where no data are available.

2 Selected methodologies implemented over Greece

Many methodologies have been developed so far worldwide [2-7], for the estimation of solar radiation and for the elaboration of solar radiation data banks where available [8,9]. The majority of global solar radiation estimation methodologies has not been tested and validated for Greece. Methodologies for the generation of Typical Meteorological Years (T.M.Y) have been adopted only for the city of Athens [10,11]. In the next sub-sections an attempt is made to review, namely to gather and present some of the above mentioned methodologies that have been implemented over Greece.

2.1 The model proposed by Jain

Jain [5] proposed a normal distribution to estimate the clear day global radiation. That was based on recorded data of hourly global radiation and sunshine duration of an eleven-year period for the city of Trieste (1972-1982) [5] and for the city of Montreal [6] (1964-1975). The proposed concept aims to fit the experimental daily radiation data on an equation like:

$$r_i = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-(t-12)^2 / 2\sigma^2\right) \quad (1)$$

where: r_i is the ratio of hourly to daily global radiation at the horizontal and t is the solar time in hours. The mean of the normal distribution is taken at solar noon and σ is the standard deviation obtained by matching the experimental recorded value of r_i at t=12h (solar noon time) in equation (1)

$$\sigma = \frac{1}{r_{t=12}\sqrt{2\pi}} \quad (2)$$

Analysing the recorded data for Trieste and Montreal Jain found that there is a linear relationship between the values of σ estimated by equation (2) and the values of theoretically calculated daylenght (S_0). Using linear regression, he proposed that σ could be estimated using the following equation:

$$\sigma = \mathrm{A}S_0 + B \quad (3)$$

where: A and B are the slope and v- intercept respectively and S_0 (hours) is the daylenght, i.e. the time between sunrise to sunset. The values of A and B are not constant. They vary from site to site and their value has to be investigated. For such investigation, detailed data for each specific region are required. For the cities of Trieste and Montreal Jain proposed the following equations to estimate σ:

for the city of Trieste $\sigma = 0.192S_0 + 0.461$ (4)

and

for the city of Montreal $\sigma = 0.209S_0 + 0.294$ (5)

When no detailed data are available the above equations of σ can be used in combination to equation (1) for the estimation of hourly global solar radiation of a site.

2.1.1 Implementation of Jain's model over Greece

Flocas [12], used the model proposed by Jain and made an attempt to predict hourly global solar radiation for six Greek cities (Rhodes, Athens, Larissa, Kavala, Agrinio and Mitilini). He also determined the standard deviation, σ, for the six cities using eq (2). The results for the city of Athens are shown in Table 2. An analysis was made using the least square equation for the regression analysis of σ. The results are shown in Table 1, while in Fig.1 the comparison between the predicted values and the measured values of hourly global solar radiation for the city of Athens for the representative month of each season is presented. The calculated values of σ using equations (6-11) for a mean value of S_o=9.5h have a maximum difference of about 7%.

Table 1. Result of the regression analysis

City	Regression equation	
Rhodes	$\sigma = 0.238S_0 + 0.159$	(6)
Athens	$\sigma = 0.203S_0 + 0.424$	(7)
Mitilini	$\sigma = 0.213S_0 + 0.398$	(8)
Agrinio	$\sigma = 0.219S_0 + 0.311$	(9)
Larissa	$\sigma = 0.201S_0 + 0.612$	(10)
Kavala	$\sigma = 0.219S_0 + 0.398$	(11)

Table 2. Long term average of σ and S_0, for Athens

Months	σ	S_0
January	2.27	9.70
February	2.62	10.58
March	2.84	11.75
April	3.07	13.01
May	3.36	14.05
June	3.31	14.58
July	3.35	14.42
August	3.21	13.42
September	2.88	12.21
October	2.75	11.96
November	2.52	9.92
December	2.37	9.40

Flocas suggests the following equation to determine σ for any site in Greece:

$$\sigma = 0.216S_0 + 0.384 \quad (12)$$

Around solar noon the fit of equation (1) in the recorded data over Greece provides a good accuracy, while a mismatch near sunset and sunrise is observed. This mismatch is due to the reason that the normal distribution is extended to infinity and not being zero at sunrise and sunset.

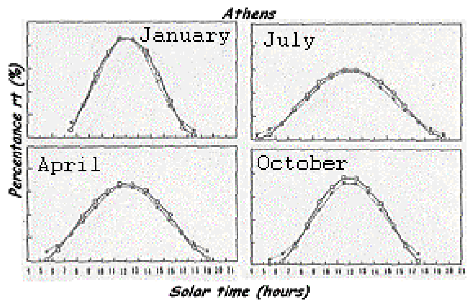

Fig. 1: Comparison of experimental values (solid line) and the theoretically calculated ones using equation (1) (dotted line)

Due to the fact that the largest amount (about the 75%) of the daily solar radiation is around solar noon, the observed mismatch near sunset and sunrise has no practical effect on the accuracy of the results.

Equation (12) can be used in combination with equation (1) for the prediction of hourly global solar radiation in any location around Greece where no detailed data are available.

2.2 The ASHRAE clear day solar flux model

ASHRAE [7], suggests the following equation for the estimation of the hourly value of the direct normal solar radiation on clear sky conditions on the horizontal:

$$I_{bn} = \frac{A}{\exp(B/\sin\alpha)} \quad (13)$$

This model also approximates the average clear – day diffuse solar flux I_d on the horizontal with the expression:

$$I_d = C.I_{bn}.F_s \quad (14)$$

where A is the apparent direct normal solar flux at the outer edge of the earth's atmosphere at zero air mass (kw/m^2), B is the apparent atmospheric extinction coefficient (dimensionless), C is the diffuse radiation factor (dimensionless) and F_s is the angle factor between the surface and the sky.

The total short wave radiation I_{TH}, reaching a terrestrial is the sum of the direct solar radiation I_{bn}, the diffuse solar radiation I_d, and the solar radiation reflected from the surrounding surfaces and from the ground, I_g.

$$I_{TH} = I_b + I_d + I_g \quad (15)$$

where: $I_b = I_{bn}.\cos\theta_z$, and θ_z is the angle between the incoming solar rays and a line normal (perpendicular) to the surface.

A and B are empirically determined from measurement of I_{bn} made on typical clear sky days. Their values vary through out the year because of seasonal changes in the dust and water – vapour content of the atmosphere and because of the changing of earth – sun distance.

2.2.1 Implementation of ASHRAE model in Athens

For the correlation of the ASHRAE constants Kouremenos et al [13] used hourly measurements of 13 years (1960-1972) performed by the National Observatory of Athens for the city of Athens. The method followed consists on selecting the maximum value of solar radiation for every hour and day of the year from the data bank. By this method the daily variation of the maximum hourly values of solar radiation is found all year round. The next step is to calculate the values of A, B, and C constants for the selected days of the year, so that the daily variation of the maximum values of hourly solar radiation, found above, can be approximated by equation (15). An iteratively estimation procedure is followed for the calculation of A, B and C. An arbitrary value is given to constant B and A, C values are estimated using the least square method, so that the daily variation of the maximum values of hourly solar radiation can be approximated by equation (15). These A and C values are used then to calculate a new value of B. This procedure is repeated until converge is obtained. The same method is applied for the 1st, 11th, and 21st day of each month of the year. Using the least square method, Kouremenos et al [13], found that the yearly variation of the constants (A, B and C) can me determine using the following equations:

$$A = \sum_{i=0}^{4} a_i D^i \qquad B = \sum_{i=0}^{4} b_i D^i \qquad C = \sum_{i=0}^{4} c_i D^i \quad (16)$$

where: D is the day of the year and the coefficients are equal to:

a_0 = 1,1048968, a_1= 0,62310300 x 10^{-3}, a_2= -0,21655676 x 10^{-4}, a_3= 0,10841363 x 10^{-6}, a_4 = -0,14720401 x 10^{-9}

b_0 = 0,12321833, b_1= -0,24593090 x 10^{-3}, b_2= 0,13219840 x 10^{-4}, b_3= - 0,67643523 x 10^{-7}, b_4 = 0,90926050 x 10^{-10}

c_0 = 0,851527187 , c_1= 1,64532521 x 10^{-4}, c_2= 1,30162335 x 10^{-5}, c_3= - 7,27912620 x 10^{-8}, c_4 = 9,86283730 x 10^{-11}

The comparison between the A, B and C values calculated using the above procedure and the ones proposed by ASHRAE [7] indicated that there is a difference of the order of 10% for A, 1% for B and 50% for C.

2.3 Angstrom formula

Angstrom [8] proposed the following formula for estimation of the global solar radiation on daily, monthly, and yearly basis:

$$\frac{H}{H_0} = a + b\frac{S}{S_0} \quad (17)$$

where: S is the sunshine duration observed (in hours), S_0 is the maximum possible sunshine duration; α and b are models parameters climatologically determined using a regression analysis, H is global solar irradiation measurement on the horizontal and H_0 is the extraterrestrial irradiation on the horizontal. The ratio S/S_0 is often called the percentage possible sunshine [14].

Angstrom method is used all over the world in order to calculate solar radiation series from measurements of sunshine duration or from short-term solar irradiation measurements.

Many researchers around the world have been involved with the estimation of the Angstrom formula constants. Black et al [15] after analyzing monthly values from various stations between latitude 30^0S and 60^0S estimated the values of a and b parameters as α=0.23 and b=0.48. Frere et al [16] taking into account various studies on the Angstrom formula constants proposed a graphical relation between the constants and the annual average value of the percentage possible sunshine (S/S_0).

2.3.1 Implementation of Angstrom formula over Greece

Flocas [14] used the method proposed by Page [17] coupling with Frere [16] graphical procedure to determine Angstrom formula constants, with ulterior aim to calculate mean monthly and annual total values of global solar radiation for 34 Greek cities. Measurements of mean monthly global solar irradiation on the horizontal made for the city of Athens by the National Observatory of Athens for the period 1961-1975 were used. Flocas also used sunshine duration measurements for 33 other sites on Greece for the same time period. He faced two main problems in his study. The first problem was that some of the stations didn't have continuous measurements for that period and the second one was that their measurements covered a shorter period. To overcome these problems he related sunshine duration in any of the 33 stations with sunshine duration in Athens. From the mean monthly values of sunshine duration in the city of Athens and from the above procedure he managed to calculate sunshine duration for each of the other 33 cities. For the same sites and from the above data the monthly and the annual values of the percentage possible sunshine (S/S_0) were calculated. These values were used to estimate global solar radiation over Greece. For the city of Athens mean monthly values of S/S_0 and H/H_0 were calculated using the recorded data. A regression analysis applied on the above values resulted the following formula:

$$\frac{H}{H_0} = 0.20 + 0.51\frac{S}{S_0} \tag{18}$$

The graphical method proposed by Frere and the annual calculated values of S/S_0 gave the following form of the Angstrom formula:

$$\frac{H}{H_0} = 0.31 + 0.41\frac{S}{S_0} \tag{19}$$

As it is easily understood values obtained by Frere graphical method can be used in Angstrom formula by reforming –0.11 for α and 0.10 for b.

To calculate mean monthly values of (H) Flocas followed two different methods. The first method (Method A) consists in using equation (18) while Method B in using equation (19).

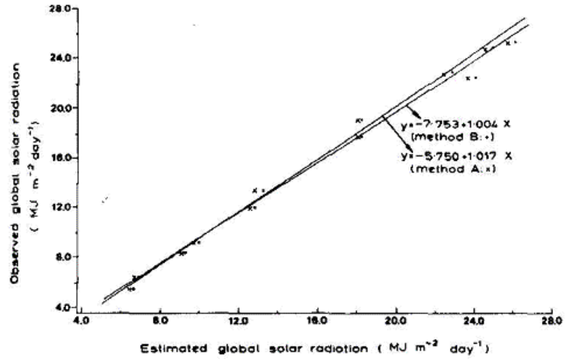

Fig. 2: Comparison of the results of the two methods in estimating global solar radiation in Athens and the observed values.

The constants values derived from the above two methods are in a good agreement with those obtained from Frere method. International literature indicates that b value could be considered as constant with a mean value of 0.52 and a standard error of 0.005, while α is a function of latitude [18]. The proposed relationship for α estimation is:

$$\alpha = 0.29\cos\phi \tag{20}$$

The α and b values estimated using Method A are in a good agreement with the above proposed mean values.

The values of average total global solar radiation (for the city of Athens) calculated using Methods A and B are 5.725 MJ/m^2 and 5.809MJ/m^2, while the measured value was 5.733MJ/m^2. Due to these results and the calculated values of the α and b constants, Method A is more advisable than Method B. As indicated above, Flocas had to face the problem of deficiency of long-term period measurements for the other 33 Greek cities. To overcome this problem he used the Frere method and the values of S/S_0. The estimated values of the α and b constants were corrected by –0.11 for α and 0.10 for b. As α and b were estimated the next step was to calculate mean monthly and annual values of total solar radiation for the 34 cities. In table 3 the estimated values for six Greek cities is shown along with the annual total solar radiation. The above calculated values and the values of the α and b, permitted the separating of Greece in three climate types regarding solar radiation, type I (subtypes Ia Ib and Ic), type II (subtypes IIa and IIb) and type III.

Table 3. a and b estimated values for 6 Greek cities

City	a	b	Annual total MJ/m^2
Rhodes	0.20	0.51	5.968
Athens	0.20	0.51	5.725
Araxos	0.20	0.51	5.474
Ioannina	0.19	0.54	4.997
Larissa	0.19	0.53	5.164
Lamia	0.19	0.53	5.273

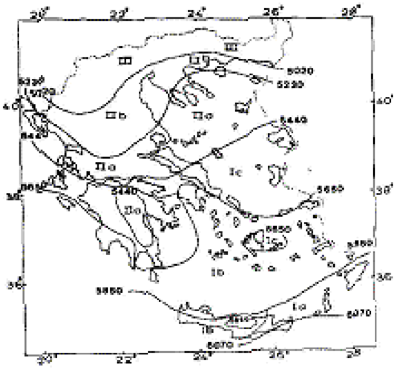

Fig 3: Climate types of Greece

2.4 Generation of T.M.Ys over Greece

Simulations of long-term performance of energy plants require detailed and accurate meteorological data as input. Where these data are available, the methodology followed is the production of Typical Meteorological Years (T.M.Y). T.M.Y or T.R.Y (Test Reference Years, a term used in USA) are datasets corresponding to a full years with hourly values covering many meteorological parameters.

2.4.1 First T.M.Y generated for Athens

The first T.M.Y (or T.R.Y) produced for the city of Athens was in 1988 by Pissimanis et al [10]. Pissimanis et al using the method proposed by Hall [9] examined 13 meteorological parameters for a time period of 17 years (1966-1982) obtained by National Observatory of Athens. The generation of the T.M.Y was done in two stages. The first stage consists on selecting five candidate years for every month of the year. This was done by comparing the cumulative distribution functions of each of the 13 meteorological parameters to their long-term performance (in all years) using the Finkelstein-Schafer method (FS). Weighted sums (WS) were produced after giving weight to the FS of every parameter. That was done due to all these parameters are not of the same importance.

Candidate years for every month of the year were those with the smallest WS values. Hall [9] recommended that the final step to be followed for the selection of the representative year of each month are the statistics of the daily values of global solar radiation and mean daily temperature. However “the final selection at the second stage was somewhat subjective, probably due to the large number of statistical parameters that had to be taken into account simultaneously”[10]. At the end of this procedure the final T.M.Y was formed and proposed. Pissimanis et al had to deal with the fact that there were no data for three of the needed meteorological parameters, but since their weighted factors were not significant they are not consider vital for the proposed T.M.Y.

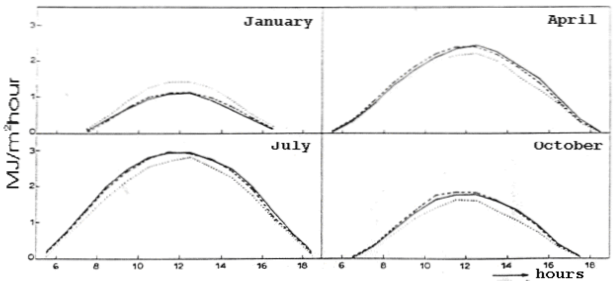

Fig.4: Mean hourly values of global solar radiation of the T.M.Y (solid lines) with their comparison to the mean values of period 1966-1982(dashed lines) for the representative month of each season (dotted lines)

2.4.2 Generation of 17 T.M.Y for Athens

Argiriou et al [11] produced 17 different T.M.Ys for the city of Athens. The aim was to select the “best” performing one using a scoring system. The scoring system, developed for the needs of that work, is based on meteorological criteria and a number of simulations of typical energy systems. For the purpose of that work hourly values of 6 meteorological parameters (global radiation, air temperature, relative humidity, wind speed, daily mean pressure and sunshine duration) were used, covering a 20 years period (1977-1996). The data used were obtained from the National Observatory of Athens. Diffuse radiation was not available for the period 1977-1989 (2.2% missing data), while the missing data for global radiation was 0.6%, and 0.1% for temperature and relative humidity. These missing data were completed using appropriate methods. Three different methods were used for the generation of 16 T.R.Ys, while a T.R.Y was developed from the average hourly value, of each meteorological parameter, from the 20-years data bank (TRY17). The methods applied for the T.R.Y production were: a) Sandia National Laboratory method [9], b) The Danish Method [19,20] and c) the Festa-Ratto Method [21]. The TMY2 method [22] could not been applied since some needed meteorological parameters were not measured by the National Observatory of Athens.

Four variations of the original Sandia National Laboratory methodology were used, leading to 12 TRYs. The first variation consists on using three sets of weighted factors (step 1 of the method) all oriented towards energy simulations applications. That produced TRY01, TRY02 and TRY03. In order to take into account all meteorological parameters (second step) in the 20-year period another variation was introduced. This variation produced TRY04, TRY05 and TRY06. The third variation of the Sandia method was used to take into account all meteorological parameters, but not weighted on an equal basis. Thus TRY07, TRY08 and TRY09 were produced. Instead of the simple selection procedure (steps 2 and 3) that Pessimanis et al proposed [10], one more variation was introduced. That consists on using a composite scoring system for each month and each parameter instead of RMSE (root mean square error). Using the last variation TRY10, TRY11 and TRY12 were produced. For the needs of the selection procedure of the Danish Method the DKTRYPC software wasused. That led to the production of two T.R.Ys, TRY15 using global radiation and TRY16 using sunshine duration. Using Festa-Ratto Method two more T.R.Ys were developed. Using the original method TRY13 was produced while a modification of the method produced TRY14. This modification consists on an effort to treat all meteorological parameter on an equal basis for the final selection. That was achieved by assigning to each candidate month a weighted sum of the distance instead of the maximum distance.

The 17 produced T.R.Ys were evaluated through the comparison of their results from various simulations for typical energy systems (a simple solar water heating system, a building, a photovoltaic system and a large scale solar heating system with interpersonal storage). The simulations software packages used were: the TRNSYS for the solar system and the building, the MINSUN code for the large-scale solar system while for the PV system the SOLCEN subroutine included in TRNSYS was used. The comparison was based on the calculation of a proper performance indicator for each energy system (solar fraction for the solar thermal system, the annual heating and cooling energy for the building and the delivered annual electric energy for the PV system). Each TRY performance was evaluated using the following procedure. The performance indicator is calculated for every energy system using each of the 17 T.R.Ys. Then an average 20-years indicator was calculated using the 20-years simulation results. Their comparison is made using the RMSE method. TRYs were rated as a function of decreasing RMSE. The maximum score is unity and assigned to the TRY with the minimum RMSE. An overall score for all TRYs is calculated adding the partial scores. Although TRY14 is the best performing one, however it is not necessarily the optimal choice of each energy system as the results show.

Table 4. Final selection of TRYs

Rank	Final Selection	Rank	Final Selection
1	TRY14	9	TRY01
2	TRY04	10	TRY02
3	TRY10	11	TRY13
4	TRY15	12	TRY17
5	TRY11	13	TRY03
6	TRY16	14	TRY05
7	TRY12	15	TRY06
8	TRY09	16	TRY08
		17	TRY07

3 Conclusions

This scientific literature review shows there is a need first to develop a network of meteorological station all over Greece, where all meteo parameters will be collected along with solar radiation. National Meteorological Service (E.M.Y) owns such a network but it is hardly accessible, while in most stations the sunshine duration is recorded instead of solar radiation.

The second, but not less significant, aim should be the implementation of the majority of the proposed methodologies for solar radiation estimation, all over Greece. Only a few methodologies have been tested and validated over Greece. These methodologies will be used in sites where no detailed data are available. The majority of these models, along with generation of T.M.Ys, have been implemented for the city of Athens.

All studies and data should be available and accessible in all scientists and professionals dealing with feasibility studies and applications of renewable energy sources. This effort should aim to indicate the most accurate methodologies over Greece along with the generation of T.M.Ys where it is possible. In this work an attempt is made to present some of the methodologies validated over Greece. There are some others fundamental works that have not been included here [23, 24 and others].

The last years an attempt is made to predict solar radiation using neural networks [25]. There should be detailed reviews of all these methods, their results, conclusions and their recommendations.

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