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ARTICLE

An Advanced Simple Method for Generating Synthetic Average Instant Hourly Solar Energy

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ABSTRACT

The main objective of this study is to generate accurate synthetic hourly solar radiation data by using an easily accessible open source data. In this regard, a new approach is proposed for estimation of synthetic hourly global solar radiation during the day by utilizing only annual solar energy data. First time in literature, a model has been developed for prediction hourly and daily solar radiation based on annual solar energy parameter in this study. Parameters of the model were generated and tested for Turkey and one of them was presented as a case study within this paper. Long term measured hourly horizontal solar irradiance data from a network of Turkish meteorological stations was used to calibrate the model function. The predictions are compared with the solar data available in literature for Turkey. The advanced simple new model is utilized in open source computer program and has the potential to be adapted to other countries.

1.Introduction

The increasing use of solar power as a source of electricity has led to increased interest in forecasting short time solar radiation. Forecasted short time solar radiation data is generally used for simulation of the solar power plants such as photovoltaic and concentrated solar power systems.[1,2] The hourly solar-radiation amount is one of the important parameters for design and efficient operation of solar-energy systems. Forecasting short time solar radiation is neither completely random nor deterministic. It is necessary to know the possible short time trend of weather data such as solar radiation, outdoor temperature and wind speed for solar power plant simulations of energy and economics.[3] In this respect, many researchers have focused on new models to generate synthetic hourly data. Laslett et al.[2] developed an algorithm to generate synthetic hourly cloudiness data for any time of the year at any location in the southwest region of Western Australia (WA). In their study, hourly cloudiness data was generated from the daily values using a first order autoregression algorithm with time varying mean and standard deviation. Yang and Koike[4] developed a numerical model to estimate global solar irradiance from upper-air humidity. In their study, a sky clearness indicator was parameterized from relative humidity profiles. Numerical model was tested at 18 sites in Japan, and hence the relationship between global solar radiation and sky clearness indicator was investigated. They found that global solar radiation strongly depends on the sky clearness indicator. Gordon Reikard[1] compared the Autoregressive Integrated Moving Average (ARIMA), Unobserved Components models, transfer functions, neural networks, and

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hybrid models to predict solar radiation at high resolution. He noticed that the best results are obtained using the ARIMA in logs, with time-varying coefficients. Chandel and Aggarwal[5] tested two models for estimation of hourly solar radiation in Western Himalayas. Many individual studies[6-9] have been carried out in recent years on testing current models for different locations of the world. Determination of the model parameters for each province is the main limitation of the synthetic hourly solar energy determination models. There is calculation model in open literature which is collecting model parameters in a simple formulation for a country. Fouilloy et. al.[10] analyzed the eleven statistical and machine learning tools tor forecasting the hourly solar irradiation. The most efficient models are determined. Anand et al.[11] tested some existing solar radiation prediction models. They compared the measured data and selected models. They proposed a new model in open literature. Ngoko et al. [12] presented a model for the synthetic generation of 1-min global solar radiation data starting from the daily clearness index. They tested the statistical characteristics of the measured and synthetic data sets.

The web page-based Solar-Med-Atlas program (URL 1) and PVGIS photovoltaic software (URL 2) are important simulation programs that predict solar energy potential and PV electricity production for many locations in the Word. These programs allow us to calculate the total energy amount per month or year. Also, there is no option to calculate the hourly synthetic solar energy amount for any chosen day. This study contributes to researchers, practitioners and energy investors to calculate the hourly probable average global solar radiation amount in a practical way by using one formulation. Researchers can utilize the formulation procedure or given formulation to write computer program about the determination of hourly solar energy amount and PV electricity production for Turkey. Synthetic average instant global solar radiation is important parameter for determination of the surface temperature of the PV systems[13]. In the present study, an advanced simple method for simulating hourly global solar radiation was developed and implemented for Turkey. Many models proposed to literature for the prediction of solar radiation are utilized existing climatic-parameters, such as cloud cover, sunshine duration, relative humidity and outdoor temperatures[14-23]. Controversially, first time in literature, a model has been developed for prediction hourly and daily solar radiation based on total annual global solar radiation parameter in this study.

To show the reliability of the model, the results are compared with the solar data available in literature for Turkey.

2. The Detrend Models for Hourly Solar Radiation

Some models that model the general distribution of hourly solar series:

2.1. Jain's Model

Jain's model[24] utilizes a Gaussian function for the solar radiation series. Model function is given below:

$$r_h = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{(h-m)^2}{2\sigma^2}\right]$$

r_h and h indicates the solar radiation and time. σ is the standard deviation of the Gaussian curve. The parameter m represents the peak hour of a day.

2.2. Baig's Model

Baig's model[25] modified the Jain's model to get better accuracy at the start and end of series. Baig's model is:

$$r_h = \frac{1}{\sigma\sqrt{2\pi}}\left\{exp\left[-\frac{(h-m)^2}{2\sigma^2}\right] + \cos\left(180\frac{(h-m)^2}{S_0-1}\right)\right\}$$

s_0 is the sunshine hour of the day at a site with latitude φ and sun's declination could be calculated by:

$$S_0 = \frac{2}{15}\cos^{-1}(-tan\varphi \cdot tan\delta)$$

δ is the angle between the rays of the Sun and the plane of the Earth's equator.

2.3. S. Kaplanis' Model

Kaplanis[26] proposes a sinusoidal function for the solar radiation series.
That is:

$$r_h = a + b \cdot \cos\left(\frac{2\pi(h-m)}{24}\right)$$

a and b in the equation are the model parameters. m is the peak hour of solar radiation.

2.4. Al-Sadah's Model

Al-Sadah[24] proposes a polynomial model in fitting hourly global radiation on a horizontal surface.
$r_h = a_1 + a_2 h + a_3 h^2$

3. New Model for Synthetic Average Instant Global Solar Radiation

The starting point of this study is the given question; Is there any relation between annual solar energy amount and hourly average solar radiation trend? In this perspective, hourly global solar radiation data taken from Turkish meteorological data stations in Turkey were analyzed. Turkey is divided into 40 regions from 1200 W / m^2 year

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to 2000 W / m^2 year with 20 W step. Changing between 19 and 40 years of total solar radiation data were analyzed. Nearly 500 000 hours of data are considered for the advanced model parameters. First of all, model parameters (a, b, c, d) are determined for each day from the first day of December. 365 function was calculated for each region. Total 14600 different functions (365 days x 40 regions) Computer program was written in python computer program. Then each model parameter of each day for 40 regions was taken to another calculation procedure. New 365 functions were determined for each day. The hourly average global radiation function was adopted to Gaussian function based on annual solar energy similar to Jain's model. End of the calculation procedure 365 functions were collected to one function. Flow diagram of the model parameters calculation procedure is given in Fig. 1.

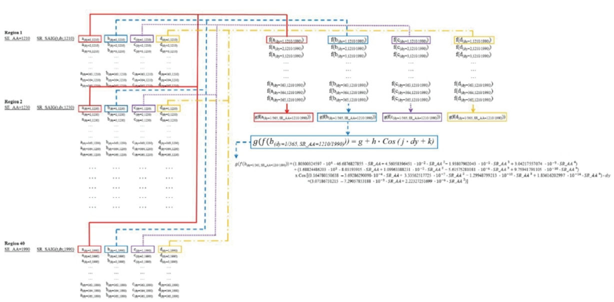

Figure 1. Flow diagram of the model parameters calculation procedure

Average global solar radiation change during the day for each location in Turkey is formulated according to time and day. The synthetic average instant global solar radiation of any time on a horizontal surface (*SR_SAIG*) in kW/m^2 can be estimated using the following equation;

$$SR\_SAIG(t,dy,SR\_AA) = a \cdot b \cdot exp \quad \frac{-(t-c)^2}{2 \cdot d^2} \tag{1}$$

In Equation (1),*dy* is the number of the day with count starting on January 1st. While the first day of January is dy = 1, for the last day of December this value is 365 in the formula. *t* indicates hour of the day. SE_AA is actual annual solar energy amount in kWh/m^2year. Model parameters for Turkey are determined for 1200 to 2000 kWh/m^2year, annual solar energy limits. The parameter to 'a' is the correction factor depending on the error rate. The parameter to 'b' represents the peak solar energy of a day. The parameter to *c* represents the peak hour of a day. The parameter to 'd' is related to slope of the function. In Equation 1, a, b, c, d are the model parameters for Turkey and can be found by the equations below:

$$a=-6.47255533646+2.64499284473\cdot10^{-2}\cdot SR_{AA}-3.68859978191\cdot10^{-5}\cdot SR_{AA2}+2.53327237263\cdot10^{-8}\cdot SR_{AA}^{3}-8.56828030062\cdot10^{-12}\cdot SR_{AA}^{4}+1.14215701185\cdot10^{-15}\cdot SR_{AA} \tag{2}$$

$$b=g+h\cdot Cos(j\cdot dy+k) \tag{3}$$

$$g=1.80300324597\cdot10^{4}-46.6876827855\cdot SR_{AA}+4.56058396451\cdot10^{-2}\cdot SR_{AA}^{2}-1.93807902043\cdot10_{-5}\cdot SR_{AA}^{3}+3.04217557074\cdot10^{-9}\cdot SR_{AA}^{4} \tag{4}$$

$$h=1.68824486203\cdot10^{3}-8.03193915952\cdot SR_{AA}+1.09963388231\cdot10^{-2}\cdot SR_{AA}^{2}-5.61575281081\cdot10^{-6}\cdot SR_{AA}^{3}+9.75941791105\cdot10^{-10}\cdot SR_{AA}^{4} \tag{5}$$

$$j=0.164780150638-3.69286290098\cdot10^{-4})\cdot SR_{AA}+3.33562517725\cdot10^{-7}\cdot SR_{AA}^{2}-1.29948799213\cdot10^{-10}\cdot SR_{AA}^{3}+1.83616202997\cdot10^{-14}\cdot SR_{AA}^{4} \tag{6}$$

$$k=3.07186731215-7.29057853188\cdot10^{-3}\cdot SR_{AA}+2.22327251699\cdot10^{-6}\cdot SR_{AA}^{2} \tag{7}$$

$$c=12.6921252445+0.21148171825\cdot Cos(0.0207537604614\cdot dy-3.73567688657) \tag{8}$$

$$d=l+m\cdot Cos(n\cdot dy+p) \tag{9}$$

$$g=-42.3695859121+0.121453134826\cdot SR_{AA}-1.21712391834\cdot10^{-4}\cdot SR_{AA}^{2}+5.33992381107\cdot10^{-8}\cdot SR_{AA}^{3}-8.63315621218\cdot10^{-12}\cdot SR_{AA}^{4} \tag{10}$$

$$m=-26.8947926096+7.27191943559\cdot10^{-2}\cdot SR_{AA}-7.15213685864\cdot10^{-5}\cdot SR_{AA}^{2}+3.07986310837\cdot10^{-8}\cdot SR_{AA}^{3}-4.88955117317\cdot10^{-12}\cdot SR_{AA}^{4} \tag{11}$$

$$n=0.555251443826-1.40928564028\cdot10^{-3}\cdot SR_{AA}+1.36740867243\cdot10^{-6}\cdot SR_{AA}^{2}-5.81017686505\cdot10^{-10})\cdot SR_{AA}^{3}+9.10938734424\cdot10^{-14}\cdot SR_{AA}^{4} \tag{12}$$

$$p=-112.640927302+0.281627123307\cdot SR_{AA}-2.67400324374\cdot10^{-4}\cdot SR_{AA}^{2}+1.11034109891\cdot10^{-7})\cdot SR_{AA}^{3}-1.6998037957\cdot10^{-11}\cdot SR_{AA}^{4} \tag{13}$$

In order to run the proposed model, the annual solar energy amount should be used. Three main parameters, namely the annual solar energy amount, time and day, are then employed to simplify the approach. The average total annual solar radiation amount for each province is provided in different web site such as Turkish State Meteorological Service's web sites. The synthetic daily average solar energy (SE_SAD) in kWh/m^2 can be estimated using the following equation;

$$\begin{aligned} SE\_SAD(t) &= \int_{5}^{21} SR\_SIG(t)\cdot dt \\ &= \int_{5}^{21} a\cdot b \\ &\cdot exp\left(\frac{-(t-c)^2}{2\cdot d^2}\right)\cdot dt \end{aligned} \tag{14}$$

As can be seen from Equation 14, synthetic daily average solar energy can be estimated by the summation of hourly solar radiation between 05:00 and 21:00. Synthetic daily average solar energy trend is calculated and given in Fig. 2 between 1300 and 2000 kWh/m^2 year. As can be seen from Fig. 2, the synthetic daily average solar energy for Turkey varies between 1 and 8 kWh/m^2 day during the year. Annual total global solar radiation map for Turkey is given in Fig. 3. Effect of model parameters for synthetic average instant global solar radiation variation during the year is shown in Fig. 4.

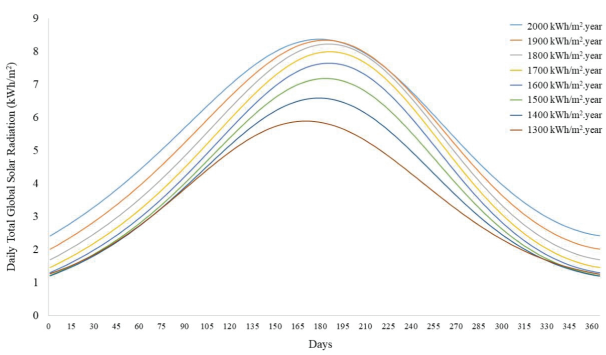

Figure 2. Daily total global solar radiation variation between 1300 and 2000 kWh/m^2 year

Figure 3. Annual total global solar radiation for Turkey

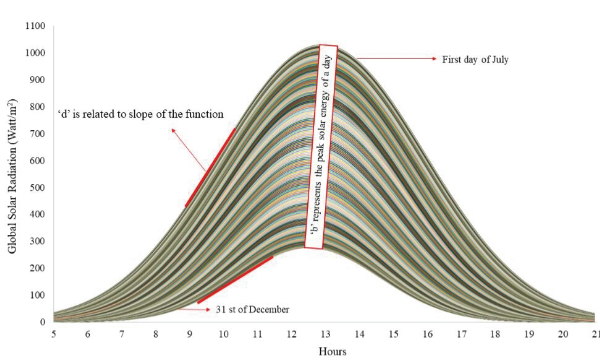

Figure 4. Synthetic average instant global solar radiation variation

Errors rate analysis was performed using the method described by Holman [25].

$$um\ Error(x_n)$$
$$= \sqrt{Error(x_1)^2 + Error(x_2)^2 + \cdots + Error(x_n)^2}$$

$$\bar{x} = \frac{Sum\ Error(x_n)}{n}$$

Here, n and is number of the test and average error rate, respectively. Average error rate was calculated for 81 providence and given in Fig. 5. The highest error rate amount is achieved in Ardahan and Ağrı. As can be seen from Fig. 4, users can determine the synthetic average instant global solar radiation during the chosen day. Annual and monthly solar energy results also compared to Solar-Med-Atlas program (URL 1) and PVGIS photovoltaic software (URL 2). Similar results are determined.

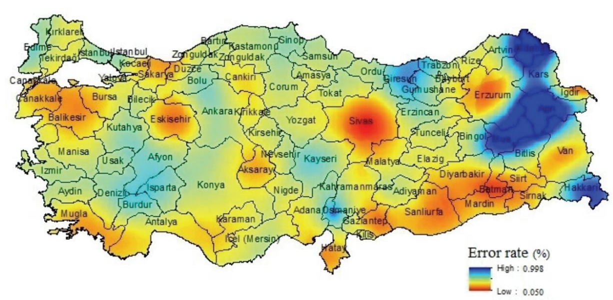

Figure 5. Map of the model error rate

4. Implementation of the Model for Turkey

The advanced simple method for synthetic average instant global solar radiation was implemented for Turkey. In order to illustrate the use of the present method, a case study was conducted for Beypazarı, Ankara in Turkey. The average annual solar energy amount (SE_AA) was 1450 kWh/m^2.year according to analyzed data.

The day and time is chosen as 15 of January and 12:00 In Equation 1, SE_AA, *dy* and *t* are 1450 kWh/m^2 year, 15 and 12, respectively. Synthetic instant global solar radiation (SR_SIG) is described as

$$SR\_SIG(t, dy, SR\_AA) = a \cdot b \cdot \left[2.71828^{\left(\frac{-(t-c)^2}{2 \cdot d^2}\right)}\right]$$

Model parameters were calculated by applying the Equation 1 to Equation 13 and given in Table 1.

Synthetic average instant global solar radiation for 12:00 can be guessed by applying the model parameters (a, b, c, d) as below

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Table 1. Model parameters for 15 of January and 12:00 in Beypazarı

Parameters	Values(-)
a	1.001791
b	279.4
c	12.51446
d	2.033152
g	582.4
h	355.57
j	0.015633
k	-2.82504
l	2.4685
m	0.45355
n	0.01814
p	-3.12935

$$SR\_SIG(12,15,1450)$$

$$= 1.001791 \cdot 279.4 \cdot \left[2.71828^{\left(\frac{-(12-12.48904)^2}{2\cdot(2.033152)^2}\right)}\right]$$

$$_{January}{}^{12:00}_{\_15}SR\_SIG_{1450\ kWh/m2.year} = 272\ Watt/m^2$$

Synthetic average instant solar radiation value for 15 January is compared to actual yearly solar radiation data. The model generated synthetic average instantaneous solar radiation values with reasonably similar statistical characteristics to the measured data in Fig. 6.

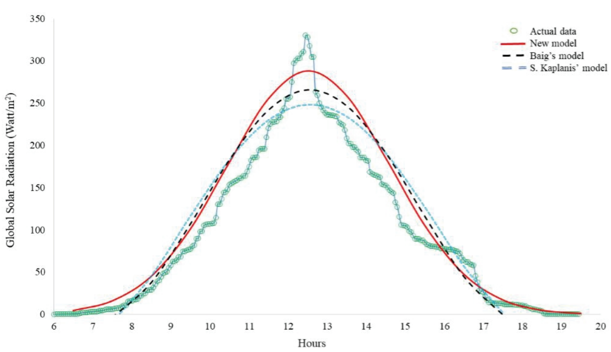

Figure 6. Comparison of new model to actual hourly data for 15 January

Screenshot photo of the written computer program in Pyton is given in Fig. 7. Solar energy amounts for any place of Turkey can easily determine any time range by utilizing written computer program.

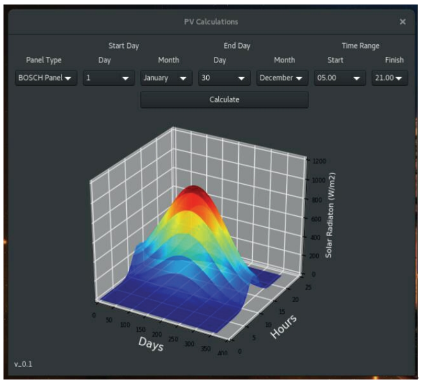

Figure 7. Synthetic average instant global solar radiation variation for Beypazarı during the year

5. Conclusion

The advanced simple method was designed to simulate solar irradiance on an hourly time scale for any location in Turkey. The results indicate that model can generate synthetic hourly horizontal radiation data with accuracies within the range of acceptable level. The comparison of the advanced simple method with the available data in the literature shows similar results. The model generated hourly solar radiation data with reasonably similar statistical characteristics to the measured data. New model has direct applicability for simulation of both thermal and PV concentrated solar power systems. Some findings of this study are as follows:

① Advanced simple method makes it possible to define the hourly solar radiation trend based on total solar radiation amount.

② A meaningful correlation was achieved between the variations of hourly solar radiation trend and annual solar energy amount in Turkey.

③ The advanced simple model is available in computer programs for solar energy calculations.

Future aim is to determine the model formulations for each county and adapted to other countries.

NOMENCLATURE

SR_AHAG	actual hourly average global solar radiation, kW/m^2
SR_ADAG	actual daily average global solar radiation, kW/m^2
SE_SAD	synthetic average daily solar energy, kWh/m^2
SE_AA	average annual solar energy, kWh/m^{2}year
SR_SAIG	synthetic average instant global solar radiation, kW/m^2
t	hour of the day.
dy	number of the day

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