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Solar energy estimation using REST2 model

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Abstract
The network of solar energy measuring stations is relatively rare through out the world. In India, only IMD (India Meteorological Department) Pune provides data for quite few stations, which is considered as the base data for research purposes. However, hourly data of measured energy is not available, even for those stations where measurement has already been done. Due to lack of hourly measured data, the estimation of solar energy at the earth's surface is required. In the proposed study, hourly solar energy is estimated at four important Indian stations namely New Delhi, Mumbai, Pune and Jaipur keeping in mind their different climatic conditions. For this study, REST2 (Reference Evaluation of Solar Transmittance, 2 bands), a high performance parametric model for the estimation of solar energy is used. REST2 derivation uses the two-band scheme as used in the CPCR2 (Code for Physical Computation of Radiation, 2 bands) but CPCR2 does not include NO_2 absorption, which is an important parameter for estimating solar energy.
In this study, using ground measurements during 1986-2000 as reference, a MATLAB program is written to evaluate the performance of REST2 model at four proposed stations. The solar energy at four stations throughout the year is estimated and compared with CPCR2. The results obtained from REST2 model show the good agreement against the measured data on horizontal surface. The study reveals that REST2 models performs better and evaluate the best results as compared to the other existing models under cloudless sky for Indian climatic conditions.
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1. Introduction
Solar power is becoming more and more popular as the oil prices keep increasing. The demand of natural resources such as coal, oil and gas continues to grow on a daily basis worldwide. These types of fuels are playing havoc in terms of global warming and increasing air pollution. So, solar power is one of the best alternatives that provide solutions of above problems [1]. Solar power is known to be one of the cleanest renewable energies today. Worldwide, electric power generation creates 40 percent of the pollution contributing to global warming, and is the fastest-growing source of such pollution.
India is located in the equatorial sun belt of the earth, thereby receiving abundant radiant energy from the sun. In most parts of India, clear sunny weather is experienced 250 to 300 days a year. In India, large areas of land are barren and sparsely populated, making these areas suitable as locations for large central power stations based on solar energy. For many solar applications, it is necessary to estimate the energy input data from available meteorological data. However, the network of solar energy measuring stations is rather scarce through out the world. In India, the hourly data of measured energy is not available, even

for those stations where measurement is done. Due to lack of hourly measured data, the estimation of solar energy at the earth's surface is required [2, 3]. Recent studies have shown that the accuracy of many broadband models of the literature is not always satisfactory, primarily because of the extreme simplicity of their parameterizations. These studies have also introduced two high-performance models to estimate direct energy. However, in most applications, it is also necessary to estimate global and diffuse energy. In this study, we have estimated direct, diffuse and global energy using REST2, a high performance model to estimate solar energy. This goal is achieved by improving the algorithms that were used to obtain the earlier two-band CPCR2 model, which have been validated by various studies. Despite good results, modeling improvements are now deemed justified by the fact that CPCR2 has been developed in the early 1980s, a period after which the fields of atmospheric radiative transfer modelling and radiative measurements have made considerable progress [4, 5]. Four important scientific achievements of the 1980–2005 period can be specifically singled out for further discussion: (i) the high-resolution absorption properties of many atmospheric gases have been obtained by spectrometry and are now described in large databases (ii) better knowledge of the optical properties of aerosols and refined modeling of their scattering effects are now available (iii) new experimental techniques and calibration procedures for the precise measurement of global and diffuse energy have emerged on the path of optimal measurement procedures, yielding significantly better accuracy under clear skies in particular, and therefore also better reference datasets for performance assessment studies; and (iv) specialized ancillary measurements describing the current atmospheric conditions are now carried out (from ground or space) more precisely, more frequently, and with a better spatial distribution than ever before, hence providing more complete and accurate inputs to the most detailed radiative models. All these factors do contribute to more efficient modeling and are appropriately used in various applications [5]. Section 2 of this paper discusses about CPCR2 and REST2 models. Section 3 presents data obtained for four proposed stations. In section 4, results are discussed and conclusion is presented in the end.

2. Models description

The accurate prediction of solar energy is essential in many solar energy applications, e.g. in photovoltaic, in solar heating of buildings etc. Beam and diffuse energy on horizontal surface should be known for accurate estimation of solar energy. However, solar energy on the top of the atmosphere is known with enough accuracy. If scattering and absorption of solar energy by different constituents of the atmosphere can be understood precisely, one can predict terrestrial beam and diffuse energy. These are the different phenomenon of attenuation of solar energy, which are showing improvement in their understanding continuously and it is resulting in new estimation models [6]. Also there is continuous improvement in solar energy instruments and measurement of atmospheric constituents like ozone, aerosols and water vapor etc., which scatter/absorb solar energy. All this is enhancing the estimation accuracy. No doubt, measured data is the best data, but it has temporal & spatial limitations. In advanced countries even, there are many stations where data is not being measured & hence such station's solar energy atlas and Typical Metrological Year (TMY) are based on modelled data [2, 7]. In the proposed study effect of two important factors namely Angstrom turbidity factor β, and Angstrom's wave exponent α has also been included. However, the values of Angstrom turbidity factor β, and Angstrom's wave exponent α are computed by Pinazo [8], by taking Angstrom's wave exponent α as 1.3. The amount of perceptible water in vertical column is computed on the basis of measured relative humidity and atmospheric temperature by using Leckner [9].

2.1 CPCR2 model (Code for physical computation of radiation, 2 bands)

This model includes parameterization of extinction processes and it requires commonly available input parameters. In this two-band clear sky solar energy modeling technique, solar spectrum is divided into two bands: Ultraviolet / Visible band, B_1, (0.29-0.7 μm) and an infrared band, B_2, (0.7- 2.7 μm). The model uses the extra terrestrial solar spectrum, as proposed by the World Radiometric Centre (WRC), with a solar constant value of 1367 Wm^{-2}. The UV/ Visible and infrared bands considered in the CPCR2 model, account for 46.04% and 50.57% of the solar constant, respectively. Therefore, coefficient f_1 = 0.4604 & f_2 = 0.5057 are to be applied to the total extraterrestrial energy, E_{on1} and E_{on2}, corresponding to bands B_1 and B_2.

2.2 Direct normal energy

It is assumed that the direct rays entering the atmosphere encounter extinction processes, which are limited to: ozone absorption, molecular scattering, uniformly mixed gases absorption, water vapor absorption, aerosol scattering and aerosol absorption. Separated extinction layers are considered, so that each band atmosphere transmittance for beam energy may be obtained by simple product of transmittances [4]. Thus, for each of two bands, the beam energy at normal incidence is given by equation (1);

$$E_{bni} = T_{Ri} T_{gi} T_{oi} T_{wi} T_{ai} E_{0ni} \tag{1}$$

where E_{bn} is the beam solar energy at normal surface (W/m^2), T_R is the rayleigh transmittance (dimensionless), T_g is the transmittance due to mixed gases (dimensionless), T_o is the transmittance of ozone (dimensionless), T_w is the transmittance of water vapor (dimensionless), T_a is the transmittance of aerosols (dimensionless), i = 1 for band B_1 and i = 2 for band B_2.
The total beam energy at ground level is given by equation (2);

$$E_{bn} = E_{bn1} + E_{bn2} \tag{2}$$

2.3 Diffuse and global energy
The diffuse energy at ground level is modeled as a combination of three individuals components corresponding to the two scattering layers (molecules and aerosols), and to a backscattering process between ground and sky [4]. The diffuse energy can be found by using equation (3);

$$E_{di} = E_{dRi} + E_{dAi} + E_{ddi} \tag{3}$$

where E_d is the diffuse energy (W/m^2), E_{dR} is the scattering due to molecules (W/m^2), E_{dA} is the scattering due to aerosols (W/m^2), and E_{dd} is the backscattering between ground and sky (W/m^2).

The global energy is given by equation (4);

$$E_g = E_d + E_b \tag{4}$$

2.4 REST2 model (Reference Evaluation of Solar Transmittance, 2 bands)
Previous results from in-depth performance assessment studies [1, 4 and 6] have shown that the CPCR2 two-band model was a top performer when compared to simpler broadband models. A recent and thorough study demonstrated that CPCR2 performed consistently well to predict direct normal energy (DNI), under both ideal and realistic conditions. The present contribution describes some new features of the model, includes its latest algorithmic improvements, and proposes a benchmark dataset for the performance assessment of this or any other similar model. The general structure of REST2 is almost identical to that of CPCR2, with a band separation at 0.7 μm. Band 1 covers the UV and visible, from 0.29 to 0.70 μm. It is characterized with strong absorption of ozone in the UV and strong scattering by molecules and aerosols over the whole band. Band 2 covers the near infrared, from 0.7 to 4 μm, and is characterized by strong absorption by water vapor, carbon dioxide and other gases, along with only limited scattering. This modeling approach has been used in a few other models of the literature and has been shown to have two interesting advantages: (i) it improves accuracy compared to regular single-band models and (ii) it simplifies the derivation of energy, whose spectral ranges correspond almost perfectly to band 1. Using the latest extraterrestrial spectral energy distribution and latest solar constant value of 1366.1 W/m^2, the extra-atmospheric energy at the mean sun-earth distance are E_{0n1} = 635.4 W/m^2 (or 46.51%) and E_{0n2} = 709.7 W/m^2 (or 51.95%) in the two bands, respectively. To the difference of CPCR2, the parameterizations for direct and diffuse energy take into account the circumsolar energy subtended in the typical total field-of-view of tracking devices [5].

2.5 Direct energy
The formalism is essentially the same as in CPCR2, except that additional provision is made for nitrogen dioxide absorption, as in REST. For each of the two-bands, i, the band direct normal energy, E_{bni}, is obtained from a product of individual transmittances;

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$$E_{bni} = T_{Ri} T_{gi} T_{oi} T_{ni} T_{wi} T_{ai} E_{0ni} \tag{5}$$

where T_{Ri}, T_{gi}, T_{oi}, T_{ni}, T_{wi}, and T_{ai} are the band transmittances for Rayleigh scattering, uniformly mixed gases absorption, ozone absorption, nitrogen dioxide absorption, water vapor absorption and aerosol extinction, respectively.
The broadband DNI is simply obtained as the sum of the two-band components;

$$E_{bn} = E_{bn1} + E_{bn2} \tag{6}$$

2.6 Diffuse and global energy
Like for CPCR2, the formalism is here also based on a two layer scattering scheme. The top layer is assumed the source for all Rayleigh scattering, as well as for all ozone and mixed gas absorption. Similarly, the bottom layer is assumed the source for all aerosol scattering, as well as for aerosol, water vapor and nitrogen dioxide absorption. After scattering has occurred in the top layer, the downwelling diffuse energy is assumed to behave as direct energy at an effective air mass, m' = 1.66. This is the air mass value that is used in calculating the transmittances dealing with absorption in the bottom layer.
The incident diffuse energy on a perfectly absorbing ground (i.e., with zero albedo) is defined as;

$$E_{dpi} = T_{oi} T_{gi} T_{0ni} T_{0wi} \left[B_{Ri} \left(1 - T_{Ri}\right) T_{ai}^{0.25} + B_a F_i T_{Ri} \left(1 - T_{ai}^{0.25}\right)\right] E_{oi} \tag{7}$$

where
$$E_{0i} = E_{0ni} \cos Z \tag{8}$$

where Z is the zenith angle.
Function F_i is a correction factor introduced to compensate for multiple scattering effects and other shortcomings in the simple transmittance approach used here. B_{R1} and B_{R2} are the forward scattering fractions for Rayleigh extinction. In the absence of multiple scattering, they would be exactly 0.5 because molecules scatter equally in the forward and backward directions. Multiple scattering is negligible in Band 2 (so that $B_{R2} = 0.5$), but not in Band 1. Using a simple spectral model to describe this effect, B_{R1} is obtained after spectral integration and parameterization as;

$$B_{R1} = 0.5\left(0.89013 - 0.0049558 m_R + 0.000045721 m_R^2\right) \tag{9}$$

The aerosol forward scatterance factor, B_a, is the same as in CPCR2;

$$B_a = 1 - \exp\left(-0.6931 - 1.8326 \cos Z\right) \tag{10}$$

The beam, diffuse and global broadband energy incident on a horizontal and ideally black surface are finally given as $E_b = E_{bn} \cos Z$, $E_{dp} = E_{dp1} + E_{dp2}$, and $E_{gp} = E_b + E_{dp}$, respectively.

Under normal conditions, a backscattered contribution must be added because of the interaction between the reflecting earth surface and the scattering layers of the atmosphere. This contribution is usually small (e.g., <10% of E_{gp}) but may become far more significant over snowy regions. The ground albedo to consider here, ρ_{gi}, refers to an average over a large zone of 5–50 km radius around the site under scrutiny, per the discussion in [4]. For each band, the sky albedo, ρ_{si}, is obtained as a function of α_i and β_i, (angstrom turbidity cofficient (dimensionless)), and the backscattered diffuse component, E_{ddi}, is derived by considering multiple reflections between the ground and the atmosphere.

$$E_{ddi} = \rho_{gi} \rho_{si} \left(E_{bi} + E_{dpi}\right) / \left(1 - \rho_{gi} \rho_{si}\right) \tag{11}$$

where $E_{bi} = E_{bni} \cos Z$. Finally, the total diffuse energy in each band is $E_{di} = E_{dpi} + E_{ddi}$, so that the broadband diffuse energy is obtained as $E_d = E_{d1} + E_{d2}$ and the broadband global energy as $E_g = E_b + E_d$.

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3. Instrumentation and data obtained

The experimental set-up for the proposed study consists of two pyranometers and one data logger. The wooden platform was used for the measurement purpose. Two pyranometers were installed, one measures the global energy and another pyranometer, provided with a shading ring, measures the diffuse energy. The output of the two pyranometers was fed to a 245-chanel data logger, which was configured to record hourly values. The measurements of global & diffuse energy at Delhi have been done by using the above experimental setup. Although the values of global energy & diffuse energy for other stations have been taken from IMD (India Meteorological Department), SEC (Solar Energy Centre, India) [10, 11].

3.1 Meteorological and solar energy data

It is necessary to obtain the hourly measured data of solar energy for different months of the year at various locations of India. The solar energy data, comprising of monthly mean hourly global and diffuse solar energy for four Indian stations, viz. New Delhi (28.58^{0}N, 77.2^{0}E, 216 m), Mumbai (19.12^{0}N, 72.85^{0}E, 14 m), Pune (18.53^{0}N, 73.85^{0}E, 559 m), and Jaipur (26.82^{0}N, 75.8^{0}E, 390 m), have been collected from India Meteorology Department (IMD) Pune and Solar Energy Centre, Ministry of New & Renewable Energy, India during the period 1986-2000 [10, 11]. The values of Angstrom turbidity factor, β, for these locations were computed by Pinazo [8], by taking Angstrom's wave exponent α as 1.3. The amount of precipitable water in vertical column is computed on the basis of measured relative humidity and atmospheric temperature by using Leckner [9].

In this particular work, the mean monthly values of global and diffuse energy for New Delhi, Pune, Mumbai and Jaipur are presented in Table 1.

4. Results

The solar energy for different months of the year by using REST2 and CPCR2 models for four Indian stations, namely New Delhi, Pune, Mumbai and Jaipur has been estimated. In the present work, monsoon months (July to September) are not included because in these months either aerosols are washed out or the particles size increase. The estimated global and diffuse energy is compared with reference data on the basis of percentage root mean square error (RMSE). A computer program in MAT LAB language is written and the measured data is given as the input along with hourly values of relative humidity and ambient temperature. The study show that REST2 model is showing maximum RMSE 3.4% and 3.1% while the CPCR2 showing maximum RMSE 9.7% and 17.6 % in the estimation of global and diffuse energy respectively under the cloudless sky. It shows that the REST2 model has evaluated better results as compared to the CPCR2 model. Table 2 shows the maximum RMSE in the estimated global and diffuse energy with the measured data for New Delhi, Pune, Mumbai and Jaipur respectively by using the REST2 and CPCR2 models.

5. Conclusions

The high-performance REST2 model is used to estimate solar energy at four stations of India. Hourly solar energy are estimated and compared with the already available CPCR2 model. The maximum error from REST2 model for estimating solar energy is 3.4% whereas from CPCR2, it is more than 10%. The main reason is that NO_2 absorption is taken into account in this study. The study revealed that REST2 models performs better and evaluate the best results as compared to the other existing models under cloudless sky for Indian climatic conditions.

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Table 1. Mean monthly global and diffuse energy for different India stations during 1986-2000

Station	Month	Global Energy ($MJm^{-2}day^{-1}$)	Diffuse Energy ($MJm^{-2}day^{-1}$)
New Delhi	January	13.52	5.21
	February	16.42	6.22
	March	20.64	7.56
	April	24.07	8.83
	May	24.43	10.68
	June	22.54	11.66
	July	19.07	11.83
	August	17.79	10.27
	September	18.90	8.27
	October	16.80	6.37
	November	14.13	4.92
	December	11.93	4.87
Jaipur	January	15.30	4.61
	February	18.02	6.10
	March	22.00	7.29
	April	25.50	8.21
	May	26.11	9.52
	June	23.94	10.78
	July	18.48	10.92
	August	17.60	10.13
	September	19.62	7.57
	October	18.17	5.41
	November	15.40	5.09
	December	13.47	4.63
Mumbai	January	16.57	6.09
	February	19.49	6.79
	March	22.24	7.17
	April	23.82	8.25
	May	23.36	9.82
	June	17.49	10.85
	July	13.45	10.45
	August	14.52	11.41
	September	16.35	10.61
	October	18.01	8.73
	November	16.60	6.63
	December	15.46	6.16
Pune	January	17.29	4.42
	February	20.58	4.77
	March	23.11	5.79
	April	24.49	6.57
	May	25.18	7.83
	June	19.32	10.99
	July	16.10	11.84
	August	15.68	11.66
	September	18.73	10.01
	October	19.25	6.70
	November	17.64	5.15
	December	16.45	4.28

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Table 2. Percentage maximum RMSE using REST2 and CPCR2 models in comparison with measured data for four Indian stations considered in this study

Station	Month	Global Energy		Diffuse Energy	
		REST2	CPCR2	REST2	CPCR2
New Delhi	January	3.4	4.2	2.1	4.0
	February	3.1	6.8	2.6	6.8
	March	2.7	3.0	3.1	6.8
	April	3.0	2.9	2.9	6.9
	May	2.1	8.2	1.8	11.4
	June	2.2	7.8	2.0	17.6
	October	1.8	4.9	2.5	10.2
	November	1.9	6.7	2.8	7.0
	December	2.6	8.5	3.1	6.7
Jaipur	January	1.8	2.8	2.8	2.0
	February	2.1	4.8	3.1	2.0
	March	1.9	3.5	3.0	3.4
	April	2.3	5.3	2.9	2.9
	May	2.8	5.0	3.1	8.9
	June	3.2	2.9	2.7	7.2
	October	3.0	4.7	1.9	7.0
	November	2.8	5.1	1.8	3.8
	December	2.7	6.0	2.0	2.8
Mumbai	January	3.0	5.1	2.4	9.5
	February	3.4	9.2	2.7	15.7
	March	2.9	7.3	3.1	13.8
	April	2.8	3.5	2.9	12.5
	May	3.1	8.1	2.8	13.6
	June	2.0	8.4	2.6	12.7
	October	1.9	8.8	1.9	9.5
	November	2.8	6.8	2.1	14.3
	December	2.6	7.6	2.3	11.6
Pune	January	2.5	5.8	2.8	3.7
	February	2.9	3.5	3.0	6.8
	March	1.7	5.3	2.9	6.5
	April	1.8	8.4	2.7	6.5
	May	1.3	7.1	2.2	14.6
	June	1.6	6.7	2.4	13.1
	October	2.6	11	2.7	15.5
	November	2.9	5.0	3.1	7.0
	December	3.4	9.7	2.9	9.8

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