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Hottel's Clear Day Model for a typical arid city - Jeddah

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ABSTRACT : *Saudi Arabia falls under the arid region and receives high intensity solar radiation throughout the year. Hottel's clear day model (proposed in 1976)is very suitable for Jeddah city since it has comparatively high visibilty and has a low altitude of 12 m. This paper implements Hottel's model for Jeddah and gives a clear comparison between the experimental values(obtained through TMY data)and the calculated values. This model is significant and notable for remote areas and developing countries which does not have sophisticated equipments for solar insolation calculation.*

KEYWORDS – *direct normal radiation, Hottel's clear day model, solar energy,*

Nomenclature

θ_z	solar zenith angle	$I_{h,d}$	global diffuse horizontal solar irradiance, W/m^2
A	Altitude	I_{on}	direct extraterrestrial normal irradiance, W/m^2
B	radiation distribution index	I_T	solar irradiance on the tilted surface, W/m^2
a, b	terms that account for the incident angle on the sloped surface	$I_{T,b}$	direct-normal (beam) component of solar irradiance on the tilted surface, W/m^2
F_1	circumsolar coefficient	$I_{T,d}$	diffuse component of solar irradiance on the tilted surface, W/m^2
F_2	brightness coefficient	$I_{T,d,iso}$	isotropic diffuse component of solar irradiance on the tilted surface, W/m^2
T_F	tilt factor	$I_{T,d,cs}$	circumsolar diffuse component of solar irradiance on the tilted surface, W/m^2
I_0	extraterrestrial irradiance, W/m^2	$I_{T,d,hb}$	horizontal brightening diffuse component of solar irradiance on the tilted surface, W/m^2
I_{sc}	solar constant, W/m^2	$I_{T,d,g}$	reflected ground diffuse component of solar irradiance on the tilted surface, W/m^2
I_{bn}	direct-normal solar irradiance, W/m^2	m	relative optical air mass,
I_h	global horizontal solar irradiance, W/m^2	R_b	variable geometric factor which is a ratio of tilted and horizontal solar beam irradiance,
$I_{h,b}$	direct-normal component of solar irradiance on the horizontal surface, W/m^2	F_{11}, f_{12}, f_{13}, f_{21}, f_{22}, f_{23}	statistically derived coefficients derived from empirical data for specific locations as a function of e

I. INTRODUCTION

Solar radiation is the main driving force for the Earth's weather and climate. It is also the prime source for renewable energy technologies. Solar energy technologies can satisfy the current energy demand and at the same time reduce anthropogenic greenhouse gas emissions. It follows from scientific and engineering research within the field that accurate terrestrial solar radiation data and derived models can improve the detection of long-term climate change, the validation of Earth radiation budget estimates, and the deployment of solar energy systems. But, accurate assessment of solar energy at the Earth's surface is difficult due to spatial, temporal and angular variability. These variations emphasise the need for localised solar radiation measurements and models[1].The power from the sun intercepted by the earth is approximately 1.8 x 10^{11} MW, which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources. Solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the unconventional energy sources. Solar energy has two other factors in the favor. Firstly, unlike fossil fuels and nuclear power, it is environmentally clean source of energy. Secondly, it is free and available in adequate quantities in almost all parts of the world where people live. Also it has no heavy mechanical section and is free from noise [2].

The modeling of the clear sky irradiance components of solar radiation is necessary in many applications of solar energy (systems design and simulation, control process of the accuracy of radiometers, data quality control, gaps filling process, etc.), as well as in routine engineering practice (e.g., the peak cooling load of buildings is determined for a hot, cloudless, summer day.) A number of models of varying complexity have been proposed in the literature, spanning from simple empirical formulae to highly sophisticated spectral codes [3]. Solar irradiance is defined as the amount of electromagnetic energy incident on a surface per unit time and per unit area. The energy emitted by the Sun passes through space until it is intercepted by planets, other celestial objects, or interstellar gas and dust. Solar irradiance includes extraterrestrial irradiance and surface irradiance. Extraterrestrial irradiance refers to the upper bound irradiance which is not affected by the aerosphere and weather conditions but depends on the Earth's rotation and revolution. Extraterrestrial irradiance is related to the latitude, the Sun elevation angle, date and the time of the day [4].

The different types of solar radiation models are listed below

- Isotropic sky (1942)
- Klucher (1979).
- Hay and Davies (1980).
- Reindl (1990).
- Muneer (1997).
- Perez et al. (1987).
- Perez et al. (1990).

1.2. Solar Radiation Models

The Total solar irradiation [5] for a surface at an angle is given by the sum of the beam component from direct irradiation and the diffuse component. The complete equation containing all diffuse components for Total solar irradiance is given by the equation

$$I_T = I_{T,b} + I_{T,d,iso} + I_{T,d.cs} + I_{T,d,hb} + I_{T,d,g} \qquad (1)$$

1.2.1 Isotropic sky model

The isotropic sky model [6, 7] is the simplest model that assumes all diffuse radiation is uniformly distributed over the sky dome and that reflection on the ground is diffuse. For surfaces tilted by an angle b from the horizontal plane, total solar irradiance can be written as

$$I_T = I_{h,b}R_b + I_{h,d}\left(1 + \frac{\cos\beta}{2}\right) + I_h\rho\left(1 - \frac{\cos\beta}{2}\right) \qquad (2)$$

1.2.2 Klucher model

Klucher [8] found that the isotopic model gave good results for overcast skies but underestimates irradiance under clear and partly overcast conditions, when there is increased intensity near the horizon and in the circumsolar region of the sky. The model developed by Klucher gives the total irradiation on a tilted plane as shown in the equation below

$$I_T = I_{h,b}R_b + I_{h,d}\left(1+\frac{\cos\beta}{2}\right)[1+F'sin^3\theta_z]\times[1+F'^{cos^2}\theta sin^3\theta_z] + I_h\rho\left(1-\frac{\cos\beta}{2}\right) \quad (3)$$

where F' is a clearness index given by

$$F' = 1-\left(\frac{I_{h,d}}{I_h}\right)^2 \quad (4)$$

The first of the modifying factors in the sky diffuse component takes into account horizon brightening; the second takes into account the effect of circumsolar radiation. Under overcast skies, the clearness index F' becomes zero and the model reduces to the isotropic model.

1.2.3 Hay–Davies model

In the Hay–Davies model, diffuse radiation from the sky is composed of an isotropic and circumsolar component [9] and horizon brightening is not taken into account. The anisotropy index A defined in the equation below represents the transmittance through atmosphere for beam radiation.

$$A = \frac{I_{bn}}{I_{on}} \quad (5)$$

The anisotropy index is used to quantify a portion of the diffuse radiation treated as circumsolar with the remaining portion of diffuse radiation assumed isotropic. The circumsolar component is assumed to be from the sun's position. The total irradiance is then computed

$$I_T = (I_{h,b} + I_{h,d}A)R_b + I_{h,d}(1-A)\left(1+\frac{\cos\beta}{2}\right) + I_h\rho\left(1-\frac{\cos\beta}{2}\right) \quad (6)$$

1.2.4 Reindl model

In addition to isotropic diffuse and circumsolar radiation, the Reindl model [10] also accounts for horizon brightening and employs the same definition of the anisotropy index *A* as described above. The total irradiance on a tilted surface can then be calculated as

$$I_T = \left(I_{h,b} + I_{h,d}A\right)R_b + I_{h,d}(1-A)\left(1+\frac{\cos\beta}{2}\right)\times\left[1+\sqrt{\frac{I_{h,b}}{I_h}}sin^3\left(\frac{\beta}{2}\right)\right] + I_h\rho\left(1-\frac{\cos\beta}{2}\right) \quad (7)$$

Reflection on the ground is again dealt with like the isotropic model. Due to the additional term in above equation representing horizon brightening, the Reindl model provides slightly higher diffuse irradiances than the Hay–Davies model.

1.2.5 Muneer model

Muneer's model is summarized by Muneer [11]. In this model the shaded and sunlit surfaces are treated separately, as are overcast and non-overcast conditions of the sunlit surface. A tilt factor T_F representing the ratio of the slope background diffuse irradiance to the horizontal diffuse irradiance is calculated from the equation below

$$T_F = \left(1+\frac{\cos\beta}{2}\right) + \frac{2B}{\pi(3+2B)}\times\left[sin\beta - \beta cos\beta - \frac{\pi sin^2\beta}{2}\right] \quad (8)$$

For surfaces in shade and sunlit surfaces under overcast sky conditions, the total radiation on a tilted plane is given by

$$I_T = I_{h,b}R_b + I_{h,d}T_F + I_h\rho\left(1-\frac{\cos\beta}{2}\right) \quad (9)$$

Sunlit surfaces under non-overcast sky conditions can be calculated using the equation below

$$I_T = I_{h,b}R_b + I_{h,d}[T_F(1-A) + AR_b] + I_h\rho\left(1-\frac{\cos\beta}{2}\right) \quad (10)$$

The values of the radiation distribution index *B* depend on the particular sky and azimuthal conditions, and the location. For European locations, Muneer recommends fixed values for the cases of shaded surfaces and sun-facing surfaces under an overcast sky, and a function of the anisotropic index for non-overcast skies.

1.2.6 Perez model

Compared with the other models described, the Perez model is more computationally intensive and represents a more detailed analysis of the isotropic diffuse, circumsolar and horizon brightening radiation by using empirically derived coefficients [12]. The total irradiance on a tilted surface is given by

$$I_T = I_{h,b}R_b + I_{h,d}\left[(1-F_1)\left(1+\frac{\cos\beta}{2}\right) + F_1\frac{a}{b} + F_2\sin\beta\right] + I_h\rho\left(1-\frac{\cos\beta}{2}\right) \quad (11)$$

Here, F_1 and F_2 are circumsolar and horizon brightness coefficients, respectively, and a and b are terms that take the incidence angle of the sun on the considered slope into account. The terms a and b are computed as

$$a = \max(0^{\circ}, \cos\theta) \quad (12)$$

$$b = \max(\cos 85, \cos\theta_z) \quad (13)$$

The brightness coefficients F_1 and F_2 depend on the sky condition parameters clearness ε and brightness Δ. These factors are defined as

$$\varepsilon = \frac{\frac{I_{h,d}+I_n}{I_{h,d}}+5.535\times10^{-6}\theta_z^3}{1+5.535\times10^{-6}\theta_z^3} \quad (14)$$

$$\Delta = m\frac{I_{h,d}}{I_{on}} \quad (15)$$

F1 and F2 are then computed as

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \left(\frac{\pi\theta_z}{180}\right) f_{13}\right)\right] \quad (16)$$

$$F_2 = f_{21} + f_{22}\Delta + \left(\frac{\pi\theta_z}{180}\right) f_{23} \quad (17)$$

The coefficients f_{11}, f_{12}, f_{13}, f_{21}, f_{22}, and f_{22} were derived based on a statistical analysis of empirical data for specific locations. Two different sets of coefficients were derived for this model [12].

II. MATERIALS AND METHODS

2.1 Hottel's model

There are many models for solar irradiance which are used to calculate the value of radiation at different locations and these models are utilized for horizontal and inclined surface [4]. For clear sky Hottel has given a simple model for evaluating transmittance of beam radiation. The elevation, day number, and the zenith angle of the location are the only required input. According to this model the atmospheric transmittance τ_b for beam radiation is given by

$$\tau_b = \frac{I_{b,n}}{I_0} \quad (18)$$

where I_b is the direct normal irradiance and I_0 is the extraterrestrial radiance. The I_0 is given by

$$I_0 = I_{sc}[1 + 0.033\cos(360N/365.25)] \quad (19)$$

and I_{sc} is the solar constant which is equals to $1367\ w/m^2$ and N is the number of day from 01 to 365.

Hottel defined the atmospheric transmittance τ_b as

$$\tau_b = a_0 + a_1 e^{-k\sec\theta_z} \quad (20)$$

where θ_z is the solar zenith angle. Therefore, the direct normal irradiance $I_{b,n}$ is now given by

$$I_{b,n} = I_0(a_0 + a_1 e^{-k\sec\theta_z}) \quad (21)$$

where a_0, a_1, and k are constants. For altitudes less than 2.5km the constants is given by

$$a_0 = 0.4237 - 0.00821(6 - A)^2 \quad (22)$$

$$a_1 = 0.5055 + 0.00595(6.5 - A)^2 \quad (23)$$

$$k = 0.2711 + 0.01858(2.5 - A)^2 \quad (24)$$

For an urban haze atmosphere, the constants are given by

$$a_0 = 0.2538 - 0.0063(6 - A)^2 \quad (25)$$

$$a_1 = 0.7678 + 0.01858(6.5 - A)^2 \quad (26)$$

$$k = 0.249 + 0.081(2.5 - A)^2 \quad (27)$$

where A is the elevation of the location above sea level in km.

III. RESULTS

3.1 Implementation of Hottel model for Jeddah, Kingdom of Saudi Arabia

In this study Solar data for Jeddah, Saudi Arab is required which is given in the table below

Table.1 Jeddah geographical matrix

Degree of longitude	39.21
Degree of latitude	21.48
Altitude above sea level	12 m
Visibility	5km > avg/year
Time Zone	AST (UTC+3)

The local data of Jeddah was used in the equations for a clear sky model by Hottel (equations 19, 21 to 24)

Average Direct normal irradiation (DNI) (eq. 21) was calculated for every day of the year and a graph was obtained (Fig. 1).

The trendline equation (equation 28) from the graph (Fig.1) could be used for prediction of DNI and could yield results close to the experimental values.

$$y = -0.0013x^2 + 0.4367x + 201.61 \qquad (28)$$

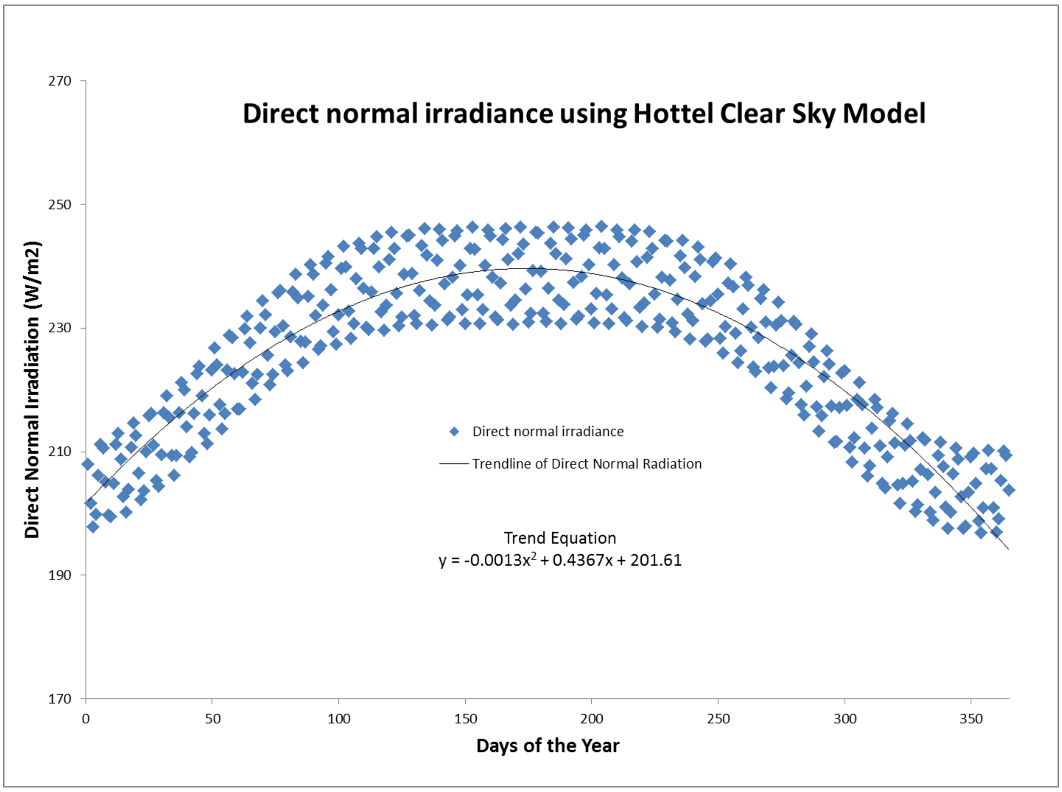

Fig.1 Hottel Clear sky Model for Jeddah

3.2 Comparison between Hottel's Model and Experimental Values

A comparison is between the values obtained using Hottel's model and Values obtained from typical meteorological year data (TMY) were plotted (Fig. 2). The blue dots indicate the average daily direct normal irradiance obtained using Hottel's model, and the red dots indicate the values obtained from TMY data of Jeddah city. An average error of 19.8 is observed between the measured and experimental values and is about 9.1%, hence it could be considered acceptable.

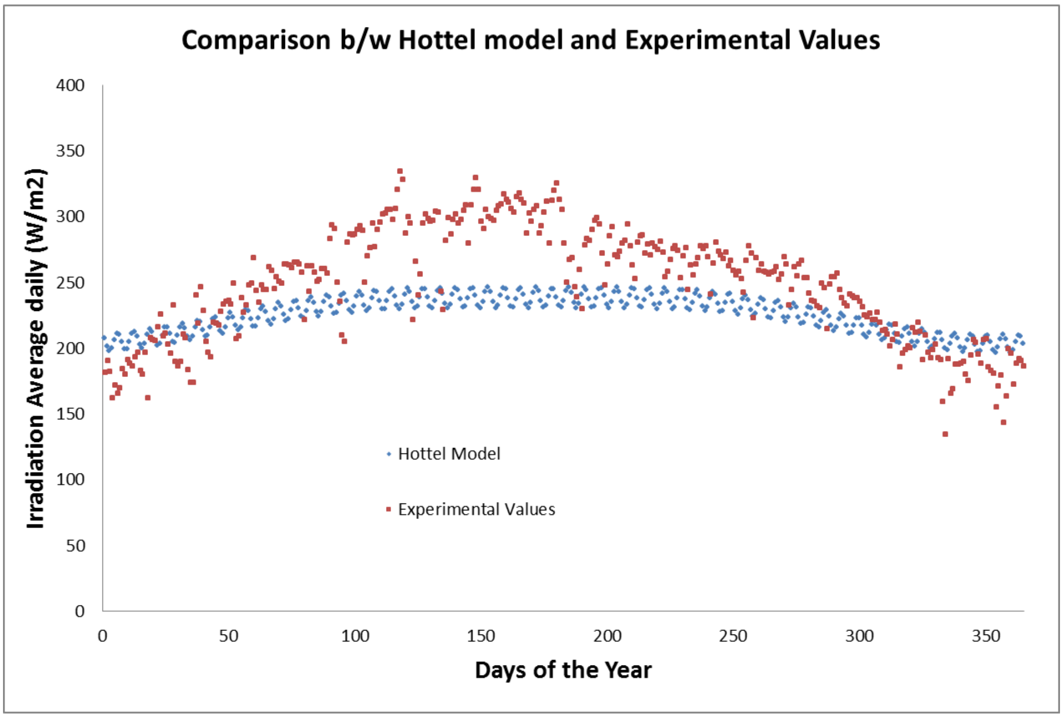

Fig.2 Comparison between Hottel's model and Experimental values

IV. CONCLUSION AND RECOMMENDATION

The results clearly show that there is not a great variation between the radiation values predicted by Hottel's model and the measured values as indicated. Although this model shows great variation in other locations, little variation in Jeddah location is observed due to stability in the weather throughout the year. With an altitude of 12m and typical desert topology of the surrounding, the city enjoys a very high visibility with an exception of desert storms once or twice a year.

There is a possibility of reducing the error in the model calculation by obtaining some correction factors to apply to the results. The use of radiation models has a great significance for places without access of basic equipment for solar measurement in many locations in the world like African countries. Incidentally these locations enjoy high solar insolation throughout the year; therefore it is all the more important to have such models for prediction of solar insolation.

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