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A Review on Plane to Array Solar Radiation Transposition Models

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Abstract : The knowledge of solar radiation for a specific location is the basis for knowing the potential and thus the beginning of the process of designing and economic and technical evaluation of the solar system, whether it is flat or concentrated, fixed or tracking, thermal or electric. Because solar radiation measurements are not available except in meteorological stations, which of course do not cover all places on the earth, the only approach to calculate the solar radiation incident on an inclined surface is by using plane – to – array transposition models for all solar radiation components: direct beam solar radiation, sky-diffuse solar radiation, and ground-reflected solar radiation. This article presents a detailed presentation of the 22 most widely used sky-diffuse transposition models in the scientific community, commercial software, and database banks specialized in solar energy. The comparison includes four different statistical indicators: RMSE, MBE, PAD and t-stat are used to identify the most promising transposition model**.**

***IndexTerms* - transposition model, solar energy, global tilted solar radiation, isotropic model, anisotropic model.**

I. INTRODUCTION

The great development taking place in the solar energy market is driven by the protection of the environment from the deterioration that may have dire consequences if we do not control it. As the energy industry sector is the most polluting among all other sectors, especially in the developing countries [1-7], attention has been drawn to increasing support in electrical energy production projects such as PV solar fields or towards projects to rationalize electrical energy consumption such as solar heaters used to heat water for industrial or domestic purposes or for house heating in cold seasons.

The knowledge of solar radiation for a specific location is the basis for knowing the potential and thus the beginning of the process of designing and economic and technical assessment of the solar system [8], whether it is flat [9] or concentrated [10], fixed [11, 12] or tracking [13,14], thermal [15-22], electrical [23-30] or both PV/T [31, 32]. Because solar radiation measurements are not available except in meteorological stations, which of course do not cover all places on the earth, the only approach to calculate the solar radiation incident on an inclined surface is by using plane – to – array transposition models (PATMs) for all solar radiation components: direct beam solar radiation, sky-diffuse solar radiation, and ground-reflected solar radiation.

The importance of the PATMs, in addition to estimating the solar radiation on any surface [33-37], lies in determining the ideal angle of inclination for the solar collectors [38,39], which would increase the productivity of the system and thus increase the profitability of the project.

Because of the importance of this topic, there are many researchers who had created these PATMs, and they are followed by researchers who had developed and still developing these models to fit the measured solar data of their regions [33]. In addition, these PATMs are used by many commercial companies specialized in the production of solar calculation programs in addition to database banks that provide weather information, including information on solar radiation components and the solar radiation incident on a surface of solar collector tilted and oriented at any tilt angle and any azimuth. An inventory of some these companies and database platforms are listed in Table 1 and Table 2 respectively [33].

Table 1
Inventory of some commercial software of solar systems and the used PATMs [33]

No	Software	Transposition model
1	NASA	Liu & Jordan
2	SOLARGIS	Muneer
3	Solcast	Reindl
4	Global solar atlas	Perez
5	SoDa	Muneer
6	Meteonorm	Hay, Skartveit & Olseth
7	Meteoblue AG	HDKR

Table 2
inventory of some database platforms and the used PATMs [33]

No	Software	Transposition model
1	EnergyPro	HDKR
2	HOMER	HDKR
3	INSEL	Liu & Jordan, Temps & Coulson, Bugler, Klucher, Hay, Willmott, Skartveit & Olseth, Gueymard, Perez and HDKR
4	PVToolbox	Liu & Jordan
5	Polysun	Hay & Davies
	PV F-chart	Liu & Jordan
6	PV*Sol	Skartveit & Olseth, HDKR and Perez
7	PVDesign	HDKR and Perez
8	PVForm	Perez
9	PVGIS	Muneer
10	PVplanner	Perez
11	PVSyst	Hay and Perez
12	PVWatts	Perez
13	RAPSIM	Unknown
14	RETscreen	Liu & Jordan
15	SAM	Liu & Jordan, Perez and HDKR
16	SimulationX	Liu & Jordan
17	TRNSYS	HDKR

Recently, Nassar et al., developed an approach for predicting the most accurate transposition model with the least error and closest to the real model based on a statistical analysis [40] [41] [42].

I. Plane to array transposition models

Transposition models require data of global horizontal (I_h) and sky-diffuse (I_{dh}) irradiation to estimate the global solar irradiance on a tilted surface (I_t). I_h is usually measured via pyranometer. Pyranometer could be used also for measuring I_{dh} by shading its eye. This is to eliminate the direct beam component by mounting a small shading disk on the pyranometer. I_h have two components: direct beam (I_{bh}) and sky-diffuse (I_{dh}), as given by [41],

$$I_h = I_{bh} + I_{dh} \tag{1}$$

The direct normal solar irradiance (I_{DN}) is given by,

$$I_{DN} = \frac{I_{bh}}{cos\theta_z} \tag{2}$$

Transposition models usually convert solar irradiance on a horizontal plane to that on a tilted one. Thus, the global irradiance for a tilted surface (I_t), at a slope angle (β) from the horizontal is given by:

$$I_t = I_{bt} + I_{dt} + I_{rt} \tag{3}$$

Equation (3) could be arranged in terms of the available data (I_{bh}) and (I_{dh}) by:

$$I_t = I_{bh}R_b + I_{dh}R_d + I_h\, R_r \tag{4}$$

The transposition factor (R_b) could be given as a function of geometrical parameters of the inclined surface and the position of the sun by:

$$R_b = max\left(0, \frac{\cos\theta_i}{\cos\theta_z}\right) \tag{5}$$

where θ_i, θ_z are the solar incidence and zenith angles respectively. Similarly, R_r is the transposition factor for ground-reflected solar irradiance. It is given by:

$$R_r = \rho_g \frac{1-\cos\beta}{2} \tag{6}$$

ρ_g is the albedo radiation factor, which is alternatively themed the ground reflectivity. It is generally assumed to equal 0.2. For a ground covered with a layer of water or with plants having glossy leaves, the reflection of such radiation is usually anisotropic. The ground transposition factor R_r is given by:

$$\mathrm{R_r} = \rho_g|\cos\psi|\left(\frac{1\text{-}\cos\beta}{2}\right)\left[1+\sin^2\left(\frac{\theta_z}{2}\right)\right] \tag{7}$$

Where ψ refers to the surface azimuth angle. The diffuse irradiance is due to scattering of the solar radiation by the different components of the atmosphere. Therefore, it has naturally non uniform distribution throughout the sky. However, some models consider diffuse irradiance uniform and isotropic. Other models try to depict the scattering processing by adding to the isotropic background, the diffuse irradiance coming from the circumsolar region and the horizon band. Therefore, the models for estimating (I_{dt}) and hence the transposition models could be divided into two groups: isotropic and anisotropic. The anisotropic group is further divided depending on the region and/or the band used in considering (I_{dt}).

2.1. Isotropic models

The isotropic sky-diffuse models assume that the diffuse sky irradiation is uniform over the sky dome. This group includes:

1. ***Liu & Jordan model,1963*:**

$$R_d = \frac{(1+\cos\beta)}{2} \tag{8}$$

2. ***Korokanis model, 1986***:

$$R_d = \frac{1}{3}(2+\cos\beta) \tag{9}$$

3. ***Jimenez & Castro model, 1986*:**

$$R_d = 0.2(1+\cos\beta) \tag{10}$$

Where the factor R_b of Jimenez & Castro model is supposed to be:

$$R_b = 0.8\frac{cos\theta_i}{cos\theta_z} \tag{11}$$

4. ***Tian model, 2001*:**

$$R_d = 1 - \frac{\beta}{180} \tag{12}$$

Where β is given in degrees

5. ***Badescu model, 2002*:**

$$R_d = \frac{(3+\cos 2\beta)}{4} \tag{13}$$

2.2. Anisotropic models

The anisotropic models assume the anisotropy of the diffuse sky radiation in the circumsolar region and the horizon in addition to the isotropic diffuse component. This group includes:

6. ***Bugler model, 1977*:**

$$R_d = \frac{1+cos\beta}{2} + 0.05\frac{I_{bh}}{I_d}R_b \tag{14}$$

7. ***Temps & Coulson model, 1977:***

$$R_d = \left(\cos^2\frac{\beta}{2}\right)(1+\cos^2\theta_i\sin^3\theta_z)\left(1+\sin^3\left(\frac{\beta}{2}\right)\right) \tag{15}$$

8. ***Steven & Unsworth model, 1979*:**

$$R_d = 0.143\left[sin\beta - \beta cos\beta - \pi\sin^2\frac{\beta}{2}\right] + \cos^2\frac{\beta}{2} \tag{16}$$

9. ***Hay model, 1979*:**

$$R_d = F_{Hay}R_b + (1-F_{Hay})\left(\frac{1+cos\beta}{2}\right) \tag{17}$$

Where: $F_{Hay} = I_{bh}/I_{ext}$ is Hay's sky-clarity factor

10. ***Klucher model, 1979*:**

$$R_d = \left(\cos^2\frac{\beta}{2}\right)(1+f_k\cos^2\theta_i\sin^3\theta_z)\left(1+f_k\sin^3\left(\frac{\beta}{2}\right)\right), \tag{18}$$

Where: $f_k = 1 - \left(\frac{I_{dh}}{I_h}\right)^2$

11. ***Modified Steven and Unsworth model, 1980***:

$$R_d = 0.51R_b + \frac{1 + cos\beta}{2} - \frac{1.74}{1.26\pi}\left[sin\beta - \beta cos\beta - \pi \sin^2\frac{\beta}{2}\right] \tag{19}$$

12. ***Willmot model, 1982*:**

$$R_d = \frac{I_{bn}R_b}{I_0} + C_\beta\left(1 + \frac{I_{bn}}{I_{sc}}\right) \tag{20}$$

Where: $I_{bn} = \frac{I_b}{cos\theta_z}$, $C_\beta = 1.0115 - 0.20293\beta - 0.080823\beta^2$, β is in radians, and $I_{sc} = 1367\, W/m^2$

13. ***Ma-Iqbal model, 1983*:**

$$R_d = k_tR_b + (1 - k_t)\left(\frac{1 + cos\beta}{2}\right) \tag{21}$$

Where k_t is the clearness index $k_t = \frac{I_h}{I_{ext}}$

14. ***Skartveit & Olseth model, 1986*:**

$$R_d = F_{Hay}R_b + Zcos\beta + \left(1 - F_{Hay} - Z\right)\cos^2\left(\frac{\beta}{2}\right) \tag{22}$$

Where $Z = max\left[\left(0.3 - 2F_{Hay}\right), 0\right]$.

Equations (17) and (22) show that the Skartveit-Olseth model is evolved from Hay model. Therefore, the performances of these models are forecasted to have a high degree of similarity.

15. ***Modified Bugler model, 1988*:**

$$R_d = \left(1 - 0.05\frac{I_{bh}}{I_d}\right)\frac{1 + cos\beta}{2} + 0.05\frac{I_{bh}}{I_d}R_b \tag{34}$$

16. ***Perez model, 1988:***

Perez model is subjected to continuous revisions. This is to improve its performance capabilities and fit the measured data more accuratel. Here in this research two versions of Perez models are investigated: Perez model 1988 and 1990. Perez model 1988 is given by,

$$R_d = F_1\frac{a}{b} + (1 - F_1)\left(\frac{1 + cos\beta}{2}\right) + F_2 \sin\beta \tag{35}$$

Where *a*, *b*, *F₁* and *F₂* are given by,

$$a = max(0, cos\theta_i) \tag{36}$$

$$b = max(cos85^o, sin\gamma) \tag{37}$$

$$F_1 = F_{11}(\varepsilon) + F_{12}(\varepsilon)\Delta + F_{13}(\varepsilon)\theta_z \tag{38}$$

$$F_2 = F_{21}(\varepsilon) + F_{22}(\varepsilon)\Delta + F_{23}(\varepsilon)\theta_z \tag{39}$$

Where $\varepsilon = \frac{\frac{I_h}{I_{dh}} + 1.041\theta_z^3}{1 + 1.041\theta_z^3}$ and $\Delta = M\frac{I_{dh}}{I_{ext}}$, θ_z is in radians and M is the optical air mass

Perez published many versions of the ***F*ij** coefficients for different locations. Table 3 in the appendix tabulates the ***F*ij** coefficients for Perez's models 1988.

Table 3

Perez sky irradiance model coefficients (1988)

ε	F_{11}	F_{12}	F_{13}	F_{21}	F_{22}	F_{23}
0-1.065	-0.196	1.084	-0.006	-0.114	0.180	-0.019
1.065-1.230	0.236	0.519	-0.180	-0.011	0.020	-0.038
1.230-1.500	0.454	0.321	-0.255	0.072	-0.098	-0.046
1.500-1.950	0.866	-0.381	-0.375	0.203	-0.403	-0.049
1.950-2.800	1.026	-0.711	-0.426	0.273	-0.602	-0.061
2.800-4.500	0.978	-0.986	-0.350	0.280	-0.915	-0.024
4.500-6.200	0.748	-0.913	-0.236	0.173	-1.045	0.065
>6.200	0.318	-0.757	0.103	0.062	-1.698	0.236

17. ***Perez model, 1990*:**

Perez model 1990 has the same equations as Perez model 1988, (35)-(39). However, the values of F_{ij} coefficients and hence F_{ij} coefficients differ from those in Table A3. Table 4 in the appendix gives the F_{ij} coefficients for Perez's models 1993.

Table 4

Perez sky irradiance model coefficients (1990)

ε	F_{11}	F_{12}	F_{13}	F_{21}	F_{22}	F_{23}
1.000-1.065	-0.008	0.588	-0.062	-0.060	0.072	-0.022
1.065-1.230	0.130	0.683	-0.151	-0.019	0.066	-0.029
1.230-1.500	0.330	0.487	-0.221	0.055	-0.064	-0.026
1.500-1.950	0.568	0.187	-0.295	0.109	-0.152	-0.014
1.950-2.800	0.873	-0.392	-0.362	0.226	-0.462	0.001
2.800-4.500	1.132	-1.237	-0.411	0.288	-0.823	0.056
4.500-6.200	1.060	-1.600	-0.359	0.264	-1.127	0.131
>6.200	0.678	-0.333	-0.250	0.156	-1.377	0.251

18. ***Modified Ma-Iqbal model, 1990*:**

$$R_d = \acute{k}_t R_b + (1-\acute{k}_t)\left(\frac{1+cos\beta}{2}\right) \qquad (40)$$

Where $\acute{k}_t$ and the optical air mass, M, are given respectively by ,

$$\acute{k}_t = \frac{k_t}{1.031 exp\left(\frac{-1.4}{0.9+\frac{9.4}{M}}\right)+0.1} \qquad (41)$$

$$M = [\cos\theta_z + 0.15(93.885-\theta_z)^{-1.253}]^{-1} \qquad (42)$$

$k_t$is as given by (21)

19. ***Muneer model, 1990*:**

$$R_d = T_M(1-F_M) + F_M R_b \qquad (43)$$

$$T_M = \left(\frac{1+cos\beta}{2}\right) + \frac{2b}{\pi(3+2b)}\left(sin\beta - \beta cos\beta - \pi\sin^2\left(\frac{\beta}{2}\right)\right) \qquad (44)$$

F_M is a composite clearness function. For shaded surface or overcast sky conditions $F_M = 0$ and $b = 2.5$, while for clear sky and partly cloudy sky conditions $F_M = F_{Hay}$, and F_{Hay} could be determined by solving the following quadratic equation,

$$F_{Hay}^2 + 0.404F_{Hay} + \left(\frac{0.987\,b}{\pi(3+2\,b)} - 0.0197\right) = 0 \qquad (45)$$

20. ***Hay, Davice, Klucher and Reindl (HDKR) model, 1990*:**

$$R_d = F_{Hay}R_b + (1-F_{Hay})\left(\frac{1+cos\beta}{2}\right)\left[1+f\sin^3\left(\frac{\beta}{2}\right)\right] \qquad (46)$$

Where $f = \sqrt{(I_{bh}/I_h)}$

21. ***Hay model, 1993***:

$$R_d = \acute{F}_{Hay} R_b + \left(1 - \acute{F}_{Hay}\right)\cos^2\left(\frac{\beta}{2}\right) \tag{47}$$

Where $\acute{F}_{Hay} = I_{bh}/I_{sc}$

This late model of Hay 1993 is the modified version of Hay's 1979. However, Hay's factor F_{Hay} in (47) is normalized to the maximum value of solar irradiance, I_{sc} .

22. ***Modified Olmo model, 1999***:

$$R_d = exp\left(-k_t\left(\theta_i^2 - \theta_z^2\right)\right)\acute{f}_c \tag{48}$$

Where θ_i and θ_z (in radians) are the incidence and solar zenith angles, respectively, k_t is the hourly clearness index, and the ρ_g is albedo of the underlying surface. The function f'_c is given by,

$$\acute{f}_c = \begin{cases} 1 - \rho_g \cos^3\frac{\theta_i}{2} & if\ 0 \le k_t < 0.35 \\ 1 - \rho_g\, sin\frac{\theta_i}{2} & if\ 0.35 \le k_t \le 0.65 \\ 1 & otherwise \end{cases} \tag{49}$$

II. Transposition models assessment

Four different statistical methods are used to assess the potential of the transposition models. This is to identify the most reliable and accurate model particularly for the area under concern. RMSE, MBE, PAD and t-stat are the tools of the comparison. Furthermore, the outputs of the different transposition models are compared with measured values, to visualize the fitting ability of each model. RMSE, MBE, PAD and t-stat are defined by [32]:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(I_{i,c} - I_{i,m}\right)^2\right]^{1/2} \tag{50}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(I_{i,c} - I_{i,m}\right) \tag{51}$$

$$PAD(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|I_{i,c} - I_{i,m}\right|}{I_{i,c}} \tag{52}$$

$$t - stat = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]^{1/2} \tag{53}$$

The statistical methods (50)-(53) could provide a logical pattern for comparing the different models. The smaller values of RMSE, PAD and t-stat indicate to more accurate are the transposition models. The equations (50)-(53) show that the results of RMSE, PAD and t-stat are positive, while MBE produce +/- values according to the deviation of the estimate from the measured values. The most promising transposition model should have the smallest values for RMSE, MBE, PAD and t-stat simultaneously. However, they may not agree simultaneously on single transposition model. Therefore, the graphical comparison is introduced to show visually the correlation between the measured values and the output of each model.

III. Conclusions

The plane to array transposition models are basic element in solar radiation estimation. It generates the solar irradiance components incident on tilted surfaces. These data are essential for assessing of any solar energy project. Solar energy software also uses a specific transposition model. Moreover, the database banks employ transposition models to generate the different solar irradiance data. Therefore, determining the suitable transposition models is elementary in order to figure out the suitable database and solar software for a certain site. This article presents the most widely used 22 planes to array transposition models. The comparison includes four different statistical indicators: RMSE, MBE, PAD and t-stat are used to identify the most promising transposition model.

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