

EVALUATION OF HOURLY TILTED SURFACE RADIATION MODELS

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Abstract—This study investigates the performance of the isotropic and four anisotropic hourly tilted surface radiation models by using monthly average hourly utilizable energy as a standard of measure. Utilizable energy is the radiation above a specified threshold level. Differences between the utilizable energy measured and the utilizable energy predicted are observed for various surface slope/azimuth orientations and critical radiation levels. Normalized root mean square difference and normalized mean bias difference statistics are formed to quantify the ability of each model to estimate the utilizable energy on a tilted surface. The influence of horizontal diffuse radiation on tilted surface model performance is examined by comparing the predicted utilizable energy on a tilted surface using both measured horizontal diffuse and estimated horizontal diffuse found from diffuse fraction correlations. On an overall basis, the isotropic sky model showed the poorest performance and is not recommended for estimating the hourly radiation on a tilted surface. The anisotropic models have comparable performance to each other. There was no significant degradation of tilted surface model performance when the diffuse radiation is estimated from a diffuse fraction correlation rather than obtained from measurements.

1. INTRODUCTION

Most collecting devices associated with solar energy systems are tilted at some angle with respect to the horizontal. Due to the lack of measured tilted surface solar radiation data, models are employed to estimate the radiation incident on a collector surface from measured horizontal radiation. Estimating the radiation on a tilted surface requires knowing the division of global horizontal radiation into its beam and diffuse components; this division may be measured or estimated from hourly diffuse fraction correlations [1-3]. In this paper, methods for calculating radiation on tilted surfaces from horizontal data are presented and evaluated.

It has been routine practice [4-9] to assess tilted surface model performance by comparing predicted total tilted surface radiation to measured total tilted surface radiation for surfaces of various slope/azimuth orientations. Usually root mean square difference (RMSD) and mean bias difference (MBD) statistics are used to quantify tilted surface model performance. Several models which account for the anisotropic behavior of diffuse radiation have been proposed and tested [7,8]. Hay and McKay [7] use a large database composed of tilted surface radiation data to compare the predictions of various models with measured data. However, comparing predicted and measured values of tilted surface radiation may not provide the best indication of model performance in the context of solar energy system simulations. In addition to comparing measured and predicted values of total tilted surface radiation, van den Brink [8] uses various reference systems (dwellings with and without active solar, swimming pools, etc.) to explore effects on the auxiliary energy required for a given system when using measured and model predicted values of total tilted surface radiation. Bugler [9] compares the calculated heat

output of a typical flat plate collector using measured and model predicted values of total tilted surface radiation. These methods of model comparisons are not general and it is difficult to extend the results to other types of collecting devices and solar energy systems.

From a solar system point of view, it is of interest to compare the ability of models to estimate the energy on a tilted surface above a specified (critical) radiation level. Klein and Beckman [10] and others have shown that utilizability is useful in predicting the performance of active, passive, and photovoltaic solar energy systems. Utilizable energy is a statistic that represents the monthly average radiation, for a specified time period, that exceeds a critical radiation level. Utilizable energy provides a means of model comparison independent of a particular system; it is used in this paper as a general method for comparing the performance of hourly tilted surface radiation models in the context of solar energy systems.

2. DATA BASE

Data from Albany, NY and San Antonio, TX provided the primary base for this tilted surface model evaluation. Additional data from four U.S. locations are used to reinforce the results from the primary data set. Table 1 lists the sites included in the data base. The data from Albany, were taken under the Solar Energy Meteorological Research and Training Sites (SEMRTS) [11] program at the State University of New York. Data from San Antonio, were taken under the SEMRTS program at Trinity University. (This data set will be referred to as the "Trinity" data.) The remaining data, identified as the "SNL" data set, were provided by Sandia National Laboratories. (Since this data set does not contain one complete year from any of the four given locations, it is not included in the primary data set.)

Table 1. Data base site summary

Site location	Primary data		SNL data			
	Albany	San Antonio	Osage City	Albuquerque	El Monte	Phoenix
Latitude	42.7°N	29.5°N	38.6°N	35.1°N	34.1°N	33.4°N
Longitude	73.8°W	98.5°W	95.8°W	106.5°W	118.0°W	112.0°W
Std. meridian	75.0°W	90.0°W	90.0°W	105.0°W	120.0°W	105.0°W
Data period (from)	1/1/79	1/1/80	12/1/86	11/1/86	12/1/86	12/1/86
Data period (to)	12/31/82	12/31/80	6/30/87	6/30/87	6/30/87	6/30/87

San Antonio and SNL locations used Eppley PSPs to monitor global horizontal and all orientations of tilted surface radiation. Eppley NIPs were used to monitor direct normal radiation. At Albany, Eppley PSP and NIP were used to monitor global horizontal and direct normal respectively. Li-Cor filtered radiometers were used for the vertical surface measurements.

The data sets have five common surface slope/azimuth orientations*: 43°S, 90°N, 90°S, 90°E, 90°W. All radiation monitoring sites used artificial horizons attached to the tilted surface pyranometers to reduce ground reflected radiation. At Albany and the SNL locations, the artificial horizons completely eliminated the ground reflected radiation ($\rho_g = 0$). At Trinity, the artificial horizons reduced the ground reflected radiation producing an effective albedo of 0.05. Global horizontal and direct normal measurements were used to calculate the horizontal diffuse radiation.

All data sets were subjected to various quality control tests. Three types of data checks were performed to identify missing data, data which clearly violate physical limits, and extreme data. Hours when the data were known to be "bad" or "missing" were omitted. Second, any hour with an observation that violated a physical limit or conservation principle was eliminated from the data set, including: reported hours with negative values of radiation, diffuse fraction greater than 1, or beam radiation exceeding the extraterrestrial beam radiation. Extreme data were identified by imposing a tolerance on the predicted values of total tilted surface radiation. The tolerance limits the absolute deviation of the predicted value of total tilted surface radiation from the measured value of total tilted surface radiation to be no greater than $200 \text{ kJ/m}^2/\text{hr} + 10\%$ of the measured total tilted surface radiation. (Approximately 2% of the data exceeded this limit.) The Hay and Davies[12] tilted surface radiation model was used to provide the predicted values of total tilted surface radiation. (Similar results were obtained when the Perez[13] tilted surface radiation model was used to provide predicted values of total tilted surface radiation.) The same tolerance was used by Hay and McKay[7] to assure that some consistency exists between values of the horizontal measured radiation (which are used for tilted surface model input) and the total tilted surface radiation measurements. To eliminate the uncertainty associated with radiation measurements at large incidence angles, hours with a zenith angle larger than 80° were eliminated. The final data set was constructed from the measured data that passed all of the quality control checks.

* Actually, the Trinity data was at a 40° slope, the Albany data at a 43° slope, and the SNL data at a 45° slope.

3. TILTED SURFACE MODELS

The total radiation on a tilted surface is composed of three elements: beam, diffuse, and ground reflected. The geometric factor R_b is the ratio of hourly (or instantaneous) beam radiation on a tilted surface to the hourly beam radiation on a horizontal surface, $R_b = I_{b,T}/I_b = \cos \theta / \cos \theta_z$.

A common method for calculating the ground reflected radiation incident on a tilted surface is to assume that the foreground in the collector field of view is a diffuse reflector and that the horizon is unobstructed. Other authors have proposed anisotropic ground reflectance models[14-16] but the lack of experimental data has hampered their validation. Therefore, the ground reflected radiation is assumed to be diffuse and is obtained by[17]

$$I_{g,T} = I\rho_g(1 - \cos \beta)/2 \quad (1)$$

where ρ_g is the ground reflectance.

Diffuse radiation is difficult to model since its spatial distribution is generally unknown and time dependent. Three diffuse subcomponents are used to approximate the anisotropic behavior of diffuse radiation: circumsolar, horizon brightening, and isotropic diffuse radiation. Circumsolar radiation is predominantly forward scattered radiation resulting from aerosols in the atmosphere. Horizon brightening is the increase in diffuse radiation near the horizon due to a larger portion (with respect to the sky dome) of the incident radiation scattering as it passes through the longer pathlength of atmosphere near the horizon and by multiple internal reflections within the earth's atmosphere. Isotropic is the remaining portion of diffuse assumed to be uniformly distributed over the sky dome. Several models have been proposed to estimate the diffuse radiation on a tilted surface (not all of which account for these three diffuse subcomponents).

Five tilted surface models are compared: isotropic[18], Hay and Davies[12], and Perez *et al.*[13] (identified by "Perez1"), Perez2[19], and a new model based on the work of Hay and Davies, Temps and Coulson[15], and Klucher[5]. In all of these models, the direction of beam radiation is accounted for by the use of R_b and isotropic ground-reflected radiation is assumed; the differences are in the treatment of diffuse radiation.

The isotropic model [18] is the simplest of the tilted surface models. This model assumes that all of the diffuse radiation is uniformly distributed over the complete sky dome. The diffuse radiation on a unit area tilted surface is given by the product of the diffuse sky radiation and the view factor from the surface to the sky, $(1 + \cos \beta)/2$.

Under completely cloudy skies, the isotropic sky model becomes a good approximation. As skies become clearer, the validity of the isotropic sky model deteriorates due to the presence of circumsolar and horizon brightening anisotropic effects.

Hay and Davies [12] developed a model (identified here as the "Hay" model) to predict the tilted surface diffuse radiation which accounts for both circumsolar and isotropic diffuse radiation. Realizing that the anisotropic behavior of circumsolar diffuse radiation becomes more pronounced under clear sky conditions, Hay and Davies defined an "anisotropy index" ($A_I = I_{bn}/I_{on} = I_b/I_o$) to weight the circumsolar and isotropic radiation components. The anisotropy index defines a portion of the diffuse radiation to be treated as circumsolar with the remaining portion considered isotropic. The circumsolar diffuse is projected onto the tilted surface in the same fashion as beam radiation.

$$I_{T,cir} = I_d A_I R_b \quad (2)$$

The remaining diffuse radiation is treated as isotropic diffuse.

$$I_{T,iso} = I_d (1 - A_I) \frac{(1 + \cos \beta)}{2} \quad (3)$$

The total diffuse radiation on a tilted surface is the sum of (2) and (3).

$$I_{d,T} = I_d \left[(1 - A_I) \left(\frac{1 + \cos \beta}{2} \right) + A_I R_b \right] \quad (4)$$

Under clear skies, the anisotropy index will be high and the circumsolar diffuse is weighted more heavily than the isotropic diffuse. Under cloudy skies, the anisotropy index goes to zero and all diffuse is treated as isotropic. This behavior is consistent with diffuse sky measurements made by Temps and Coulson [15] (and others as given in Hay and McKay [4]).

The Perez [13] model incorporates all three sub-components to account for circumsolar diffuse, horizon diffuse, and isotropic diffuse radiation. The circumsolar region has a half angle of 25° and the horizon region is assumed to be infinitesimally thin at a 0° elevation. The contribution of diffuse radiation from the circumsolar, isotropic, and horizon regions is determined by two empirically derived coefficients ("reduced brightness coefficients"). The empirical coefficients are based on two years of data each from Carpentras and Trappes, France. (Part of the Albany dataset was used in verification of this model.)

The Perez2 [19] model uses a point source circumsolar region with empirical coefficients derived from five U.S. locations (approximately 42 months of data). The complete versions of the two Perez models will not be presented here; the reader is referred to [13] and [19] for details.

A new tilted surface model has been developed. The Hay model does not account for horizon brightening diffuse radiation. Preliminary calculations of diffuse radiation incident on south facing surfaces indicated that the Hay model underpredicted the tilted surface diffuse radiation. The Hay model may be improved by the addition of a horizon brightening term.

In their study of clear sky radiance distributions, Temps and Coulson [15] approximated the horizon brightening effects by applying a correction factor of $[1 + \sin^3(\beta/2)]$ to the isotropic diffuse radiation. In other words, the isotropic diffuse multiplied by the above correction factor accounted for both isotropic diffuse and horizon brightening diffuse radiation. The correction factor pertained to clear sky conditions only. Klucher [5] modified the Temps and Coulson clear sky model by imposing a modulating factor, $F = 1 - (I_d/I)^2$ on the sine term. The Klucher form of the correction factor is $[1 + F \sin^3(\beta/2)]$. This factor F forced the anisotropic correction factor to approach unity under cloudy sky conditions so that the model reduces to the isotropic sky model.

The horizon brightening correction factor used by Temps and Coulson was applied to the isotropic term in the Hay model. Various modulating functions† were applied to the horizon brightening correction factor. The factor $f = \sqrt{I_b/I}$ was determined to be the best function for modulating the horizon brightening diffuse correction term (the Klucher correction factor, F , had similar performance). The new anisotropic model becomes

$$I_{d,T} = I_d \left[(1 - A_I) \left(\frac{1 + \cos \beta}{2} \right) \times (1 + f \sin^3(\beta/2)) + A_I R_b \right] \quad (5)$$

The first term in brackets represents the isotropic diffuse radiation corrected to include horizon brightening diffuse radiation. The second term represents the contribution of circumsolar diffuse radiation. Under cloudy skies, the modulating factor and the anisotropy index go to zero and the model reverts to the isotropic model. Under partly cloudy skies, both the modulating function and anisotropy index are non-zero.

4. BASIS OF COMPARISON

To design and optimize solar energy systems, long term estimates of system performance are required.

† The form of the modulating functions was selected by recognizing that the horizon brightening is diminished under cloudy sky conditions. Factors that provide some indication of the sky conditions were applied to the horizon brightening term. The factors include $F = 1 - (I_d/I)^2$, $\sqrt{I_b/I}$, and $\sqrt{A_I}$.

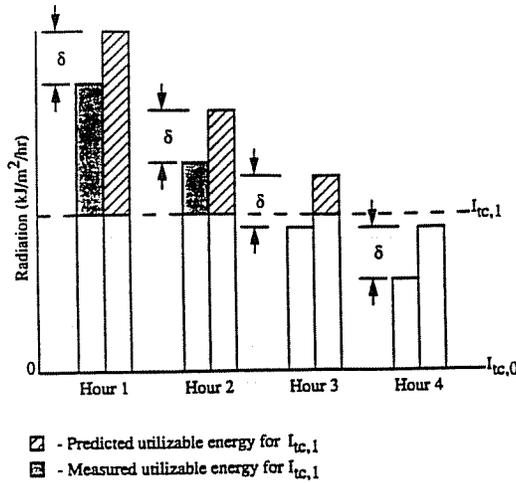


Fig. 1. Hourly radiation sequence; if critical radiation level is at $I_{tc,0}$, all hours are utilizable. If critical radiation level is at $I_{tc,1}$, only the shaded portions of the hour are utilizable.

Utilizability methods are effective for predicting the performance of a variety of solar energy systems (Klein and Beckman [10]). To assess the impact of the uncertainty in a tilted surface model on predicted solar energy system performance, hourly utilizable energy is used to compare tilted surface radiation models. Since energy system performance over long time periods is of interest, monthly average hourly utilizable energy is an appropriate quantity for model comparisons.

Throughout the remainder of this paper when utilizable energy is mentioned, monthly average hourly utilizable energy for a particular hour, e.g. 10–11 a.m., is implied. The monthly average hourly utilizable energy is given by

$$UE = \frac{1}{N} \sum_N (I_T - I_{T,c})^+ \quad (6)$$

where N is the number of radiation observations included in the summation, I_T is the total (beam, diffuse, and ground reflected) radiation on a tilted surface (measured or predicted) for the hour in question, $I_{T,c}$ is the critical radiation level, and the + indicates that only positive differences are summed.

The measured utilizable energy and model predicted utilizable energy for various surface slope/azimuth orientations over a range of critical radiation levels at each surface orientation for a given hour are available. Individual model performance is quantified by a normalized root mean square difference ($NRMSD$) and a normalized mean bias difference ($NMBD$).

* Because tilted surface measurements are not without error, the nomenclature root mean square difference and mean bias difference is used rather than root mean square error and mean bias error.

$$NRMSD = \left[\frac{1}{m} \sum_m (UE_{meas} - UE_{pred})^2 \right]^{1/2} / \overline{UE}_{meas} \quad (7)$$

$$NMBD = \frac{1}{m} \sum_m (UE_{meas} - UE_{pred}) / \overline{UE}_{meas} \quad (8)$$

where: m is the total number of monthly average hourly utilizable energy values included in the statistic, UE_{meas} is the utilizable energy measured, UE_{pred} is the utilizable energy predicted by a given model, and \overline{UE}_{meas} is the measured utilizable energy averaged over m values.

The results are based on monthly average hourly utilizable energy for the hour 10–11:00 a.m. This hour was selected to be representative of energy utilizable by a solar energy system over a complete year. The authors carried out similar analysis for the hour 11–12:00 and found comparable results with 10–11:00. Whillier [20] showed that for most locations, over the long term, solar radiation is approximately symmetric about solar noon. Both Whillier and Liu and Jordan [21] have shown that utilizability is essentially the same for all hours in a given month. The combination of these observations indicate that similar results will be obtained if this analysis was applied to other hours in the day.

Differences between utilizable energy and traditional hourly model comparison techniques will be illustrated by example. Figure 1 represents a sequence of measured and predicted hourly radiation. The shaded regions above the critical level $I_{tc,1}$ represent the utilizable energy for the hour. δ is the difference

Table 2. Tilted surface model critical radiation levels

Location	Slope	I_{tc} (increment), $\text{kJ m}^{-2} \text{hr}^{-1}$
Albany, 1979*	43°S	0–2500 (500)
	43°S	0–2500 (500)
	90°S	0–1500 (500)
	90°W	0
	90°E	0–500 (500)
Albany, 1981–82	43°S	0–2500 (500)
	90°S	0–1500 (500)
	90°W	0
	90°E	0
	90°N	0
Trinity, 1980	43°S	0–2500 (500)
	90°S	0–1000 (500)
	90°W	0
	90°E	0–500 (500)
	90°N	0
SNL	43°S	0–2500 (500)
	90°S	0–1000 (500)
	90°W	0
	90°E	0
	90°N	0

* Vertical surface measurements were not available for Albany, 1979.

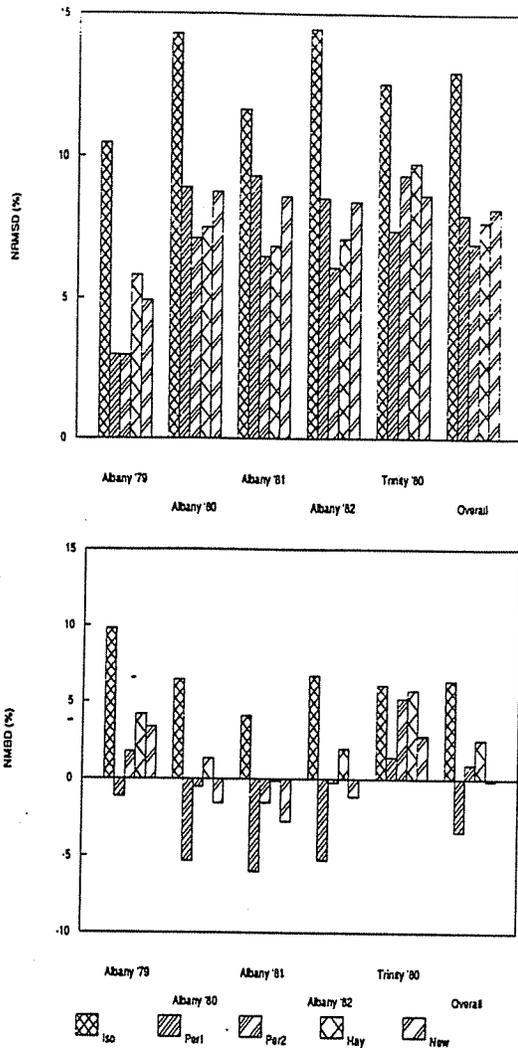


Fig. 2. *NRMSD* and *NMBD* for all surface orientations and critical radiation levels given in Table 2, 10–11:00 a.m.

between the measured and predicted radiation. Traditional hour by hour comparisons compute the *RMSD* and *MBD* based on each hourly δ and all hours in the sequence are used. In contrast, the utilizable energy approach is only concerned with those hours that exceed the critical radiation level. When the critical radiation level is at zero, all the hours in this sequence would be used in forming the monthly average utilizable energy. If the critical level is at $I_{c,1}$, the fourth hour would not be used in forming the measured and predicted monthly average hourly utilizable energy although a difference δ between the measured and predicted energy still exists. The utilizable energy approach is less sensitive to hourly differences between measured and predicted radiation because the measured and predicted radiation values are averaged over a month prior to taking their difference. Thus, the *NRMSD* and *NMBD* numerical results from hour by hour and monthly average utilizable energy model comparisons

will not be the same and the relative ranking of a model as determined by the two methods may differ.

The influence of critical radiation level on model comparison results will also be illustrated by example. If the sequence of hours in Fig. 1 are viewed as monthly average hourly quantities, the shaded regions represent the monthly average hourly utilizable energy measured and predicted. δ is the difference between the measured and predicted monthly average hourly utilizable energy. If δ is normalized by the utilizable energy measured, a nondimensional fraction results. As the critical level increases, the data set used in determining *NRMSD* and *NMBD* decreases in size as hours of low radiation do not contribute to utilizable energy and the normalizing factor (utilizable energy measured) decreases causing the normalized difference to increase (for constant δ). Thus, small normalized differences at low critical radiation levels translate to large normalized differences at high critical radiation levels.

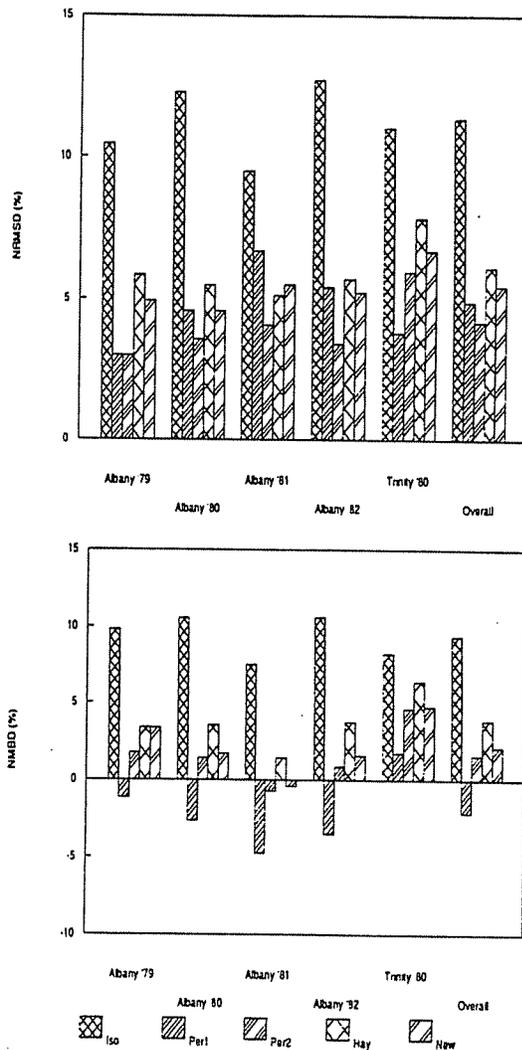


Fig. 3. *NRMSD* and *NMBD* for south-facing surface orientations and critical radiation levels given in Table 2, 10–11:00 a.m.

Under these circumstances, the relative ranking of models may well be a function of the critical radiation level.

5. RESULTS

The *NRMSD* and *NMBD* statistics are formed using all surface slope/azimuth orientations over a range of critical radiation levels. The inputs to the tilted surface models are measured values of global horizontal and direct normal radiation. Table 2 shows the surface orientations and critical levels used in forming the *NRMSD* and *NMBD* statistics. The maximum critical radiation level for a given orientation and data set was limited to values in which utilizable energy would be produced for all months. The resulting *NRMSD* and *NMBD* statistics for each model and all surface orientations are shown in Fig. 2 for the hour 10–11:00 a.m. The *NRMSD* results indicate that the anisotropic models (Hay, Perez1, Perez2, and new model) show similar performance on an overall basis (within 1.5%) but the isotropic model exhibits much larger differences from the utilizable energy measured. The *NMBD* results show the isotropic model substantially underpredicts the utilizable energy and the Perez1 model considerably overpredicts the utilizable energy on an overall basis.

In the northern hemisphere, most collecting devices for solar energy systems are oriented south facing. It is useful to observe model performance when applied only to south-facing surface orientations. The *NRMSD* and *NMBD* statistics are calculated using the two available south facing surface orientations (43°S and 90°S) at the critical levels for these two orientations indicated in Table 2. The results are shown in Fig. 3.

On an overall basis, the *NRMSD* was reduced by approximately 2% for each model and the anisotropic models are within 2% of each other. The *NMBD* revealed some interesting results. When compared to all surface orientations, the *NMBD* for the isotropic model is larger for south facing indicating that the model overpredicts the tilted surface utilizable energy on non-south-facing surface orientations. The margin of overprediction by the Perez1 model is reduced for south facing surfaces when compared to its performance for all surface orientations. The *NMBD* for the Perez2 model is nearly the same for south facing and all surface orientations. The Hay and new model have larger underpredicting differences for south-facing surfaces indicating that these models overpredict tilted surface utilizable energy on non-south orientations. Another *NMBD* peculiarity is noted in the Trinity results. All models underpredict the utilizable energy at Trinity. This may be due to uncertainty in the reported value of effective ground reflectance associated with the artificial horizons. A value of ground reflectance $\rho_g = 0.05$ is reported but if the actual reflectance was higher, the measuring instrument would receive more energy due to ground reflectance causing the measured utilizable energy to be higher.

In the remaining cases, the year-to-year and location-to-location results are similar to those already shown. Thus, only the overall results are tabulated and presented in Table 3.

To observe the effects of critical radiation level on model performance, *NRMSD* and *NMBD* statistics are shown in Fig. 4 for a 43° south-facing surface at critical levels ranging from 0 to 2500 kJ/m²/hr. In general, both the *NRMSD* and *NMBD* increased for each model because the normalizing factor, the average utilizable

Table 3A. Overall *NRMSD* results for Albany and Trinity locations

Case	<i>NRMSD</i> (%)				
	Isotropic	Perez1	Perez2	Hay	New
All orientations	12.98	7.94	6.94	7.69	8.16
South-facing orientations	11.37	4.88	4.18	6.11	5.45
43° S surface, $I_{tc} = 0$	6.19	1.53	1.84	3.18	2.70
90° S surface, $I_{tc} = 0$	9.04	6.31	4.94	5.21	5.09
All orientations*	14.59	7.63	7.03	8.00	8.17
South orientations*	13.17	5.57	4.76	6.58	5.99

Table 3B. Overall *NMBD* results for Albany and Trinity locations

Case	<i>NMBD</i> (%)				
	Isotropic	Perez1	Perez2	Hay	New
All orientations	6.38	-3.43	0.92	2.54	-0.12
South-facing orientations	9.35	-2.13	1.58	3.85	2.12
43° S surface, $I_{tc} = 0$	5.86	-0.52	1.37	2.83	2.33
90° S surface, $I_{tc} = 0$	5.44	-3.61	0.84	2.28	-1.23
All orientations*	7.67	-3.35	0.92	2.89	-0.12
South orientations*	10.57	-2.51	1.21	3.81	1.92

* The Orgill and Hollands correlation was used to estimate horizontal diffuse radiation.

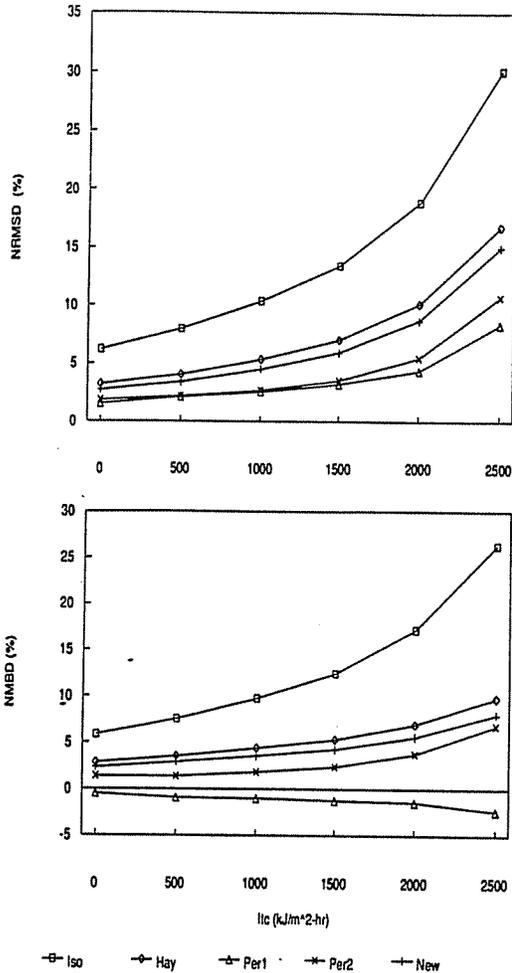


Fig. 4. Influence of critical radiation level on *NRMSD* and *NMBD* for 43°S 10-11:00 a.m.

energy measured, is reduced at higher critical radiation levels. At the higher critical radiation levels, the Perez1 and Perez2 models performed better than the Hay or new models on an overall *NRMSD* basis. The *NMBD* results show that the isotropic, Perez2, Hay, and new model underpredict the utilizable energy while the Perez1 overpredicts.

The effect of changing the surface slope from 43°S to 90°S was also investigated. The *NRMSD* and *NMBD* statistics for a 90° south-facing surface and critical radiation level of 0 are compared with the results from 43°S in Table 3. The Perez1 model showed a substantial increase in the *NRMSD*. The increase in *NRMSD* coupled with the *NMBD* results indicates that Perez1 overpredicts the utilizable energy by a greater margin for a south-facing vertical surface than a 43° surface. The *NMBD* results also show that the new model overpredicts the utilizable energy for south-facing vertical surfaces.

It is clear that the anisotropic models perform better than the isotropic model but there is not one particular anisotropic model that consistently outperforms the

others. For example, the results for all orientations in Table 3 show the Perez2 has the lowest *NRMSD* but the new model has the lowest *NMBD*. For the 43°S surface results given in Fig. 4, Perez1 has the lowest *NRMSD* and *NMBD* over the range of critical radiation levels but for a 90°S surface at Albany 1980 (Fig. 5) the new model has the lowest *NRMSD* and *NMBD*. In general on an overall basis, the anisotropic models show similar performance.

In cases when measured direct normal (or horizontal diffuse) radiation is not available, correlations must be used to estimate the hourly direct normal (or horizontal diffuse). To explore the effects of using a diffuse fraction correlation on the resulting utilizable energy predicted by each tilted surface model, the Orgill and Hollands[1] hourly diffuse fraction correlation is used to predict the diffuse radiation on a horizontal surface (given measured global horizontal radiation). The *NRMSD* and *NMBD* statistics are formed for each location using the surface orientations and critical levels (Table 2), and compared to statistics based on using measured diffuse radiation. The overall results (Table

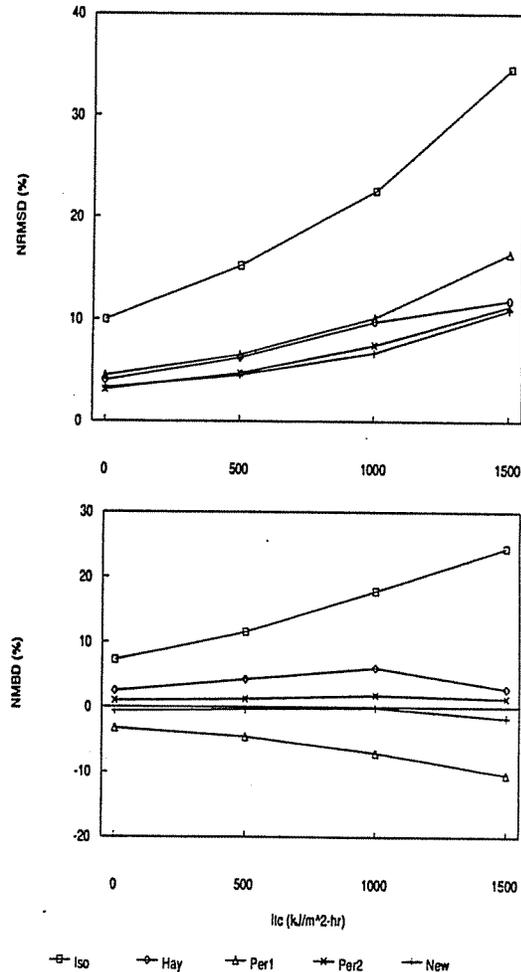


Fig. 5. Influence of critical radiation level on *NRMSD* and *NMBD* for 90°S surface for Albany 1980, 10-11:00 a.m.

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New
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5.45
2.70
5.09
8.17
5.99

New
-0.12
2.12
2.33
-1.23
-0.12
1.92

3) showed no significant difference in the utilizable energy predicted when using the Orgill and Hollands correlation to estimate the diffuse radiation on a horizontal surface for input to the tilted surface models.

Additional data provided in the SNL data set which includes four locations with approximately six months of data from each location was available for model comparisons. *NRMSD* and *NMBD* results from these four locations are included here to reinforce the results previously presented. The results for south-facing surfaces are given in Fig. 6. On an overall basis, the Hay model performs the best at the SNL locations (even though coefficients for the Perez2 model were derived, in part, from data at these SNL locations).

The anisotropic tilted surface models showed similar performance in both *NRMSD* and *NMBD* statistics. The choice for the "best" model is influenced by the limitations and relative complexity of the individual model. The Hay and new model are simpler to use when compared to the Perez models. The Perez models also have the potential for being location dependent due to the empirical nature of the reduced brightness coefficients; however, recent research noted that location dependence of this model was negligible [19]. The Hay model does not include any empirical coefficients. A problem related to all anisotropic models is determining the transmittance-absorptance product.[§]

6. CONCLUSIONS

Four existing models for estimating the diffuse radiation on a tilted surface were presented and evaluated in this paper. The models include: isotropic, Hay, Perez1, and Perez2. A fifth model was developed by modifying the Hay model to include horizon brightening. Monthly average hourly utilizable energy is used as a metric for model performance evaluation. Each model uses the same method for calculating beam and ground reflected radiation on a tilted surface; the differences are in the treatment of the diffuse radiation.

On an overall basis, the isotropic model showed the poorest performance and should not be used for estimating the hourly diffuse radiation on a tilted surface. The four anisotropic models all showed comparable performance. The Hay and new model are simpler to use when compared to the Perez models. The Hay or new model would be useful in performing computa-

[§] It is necessary to modify the traditional methods e.g. [17] for calculating the transmittance-absorptance product ($\tau\alpha$) of a glazing system when using anisotropic models. For the Hay, Perez2 and new models, the authors recommend treating the circumsolar diffuse and isotropic diffuse separately. The ($\tau\alpha$) product for circumsolar radiation should be calculated as if it were beam radiation. The effective angle for isotropic diffuse (and isotropic/horizon diffuse term in eqn (5)) can be calculated as given in Duffie and Beckman [17]. These recommendations do not apply to the Perez1 model which requires further investigation due to the large size of the circumsolar region.

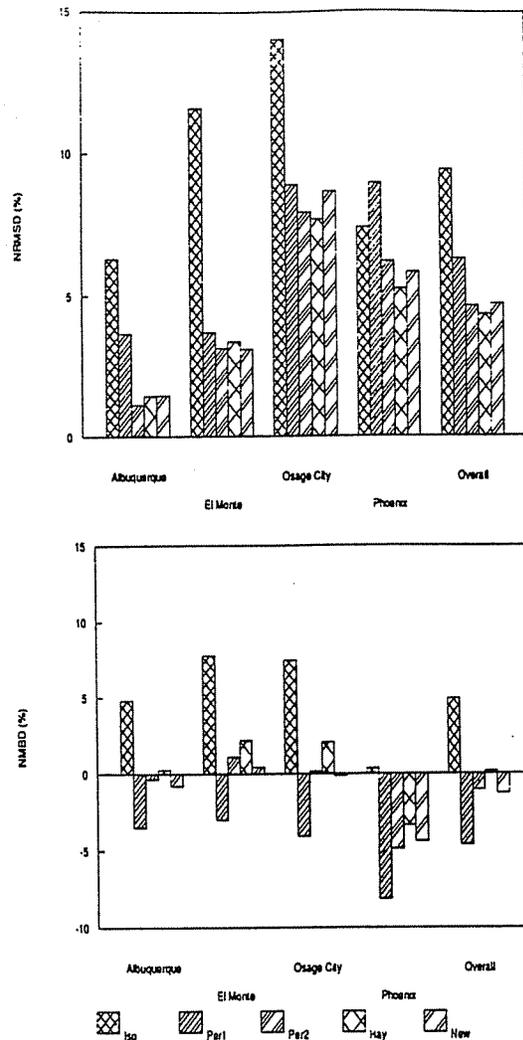


Fig. 6. SNL locations *NRMSD* and *NMBD* for south-facing surface orientations and critical radiation levels given in Table 2, 10-11:00 a.m.

tions with a hand-held calculator. The added relative complexity of the Perez models should not be a problem in computer-aided calculations. The Perez2 model performed marginally better than the Perez1 model.

The influence of diffuse radiation on the performance of each tilted surface model was investigated by using the Orgill and Hollands diffuse fraction correlation to estimate the horizontal diffuse radiation for input to the tilted surface models. From a utilizable energy standpoint, the tilted surface models showed little sensitivity to the method for determining horizontal diffuse radiation.

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NOMENCLATURE

A_l	Anisotropy index
f	Modulating function
I	Hourly total horizontal radiation, $\text{kJ}/\text{m}^2 \text{ hr}$
I_b	Hourly horizontal beam radiation, $\text{kJ}/\text{m}^2 \text{ hr}$
$I_{b,T}$	Hourly tilted surface beam radiation, $\text{kJ}/\text{m}^2 \text{ hr}$
I_{bn}	Hourly normal incidence beam radiation, $\text{kJ}/\text{m}^2 \text{ hr}$
I_d	Hourly horizontal diffuse radiation, $\text{kJ}/\text{m}^2\text{-hr}$
$I_{d,T}$	Hourly tilted surface diffuse radiation, $\text{kJ}/\text{m}^2\text{-hr}$
$I_{g,T}$	Hourly ground reflected radiation on a tilted surface, $\text{kJ}/\text{m}^2\text{-hr}$
I_o	Hourly horizontal extraterrestrial radiation, $\text{kJ}/\text{m}^2\text{-hr}$
I_{on}	Hourly normal incidence extraterrestrial radiation, $\text{kJ}/\text{m}^2\text{-hr}$
I_T	Hourly total tilted surface radiation, $\text{kJ}/\text{m}^2\text{-hr}$
I_{Tc}	Critical radiation level, $\text{kJ}/\text{m}^2\text{-hr}$
$I_{T,cir}$	Circumsolar contribution to tilted surface radiation, $\text{kJ}/\text{m}^2\text{-hr}$
$I_{T,iso}$	Isotropic contribution to tilted surface radiation, $\text{kJ}/\text{m}^2\text{-hr}$
I_T	Hourly total tilted surface radiation, $\text{kJ}/\text{m}^2\text{-hr}$
m	Number of monthly average hourly utilizable energy values
N	Number of radiation observations
$NMBD$	Normalized mean bias difference, %
$NRMSD$	Normalized root mean square difference, %
R_b	Geometric factor for beam radiation
UE	Monthly average hourly utilizable energy
UE_{meas}	Monthly average hourly utilizable energy using measured tilted surface radiation
UE_{pred}	Monthly average hourly utilizable energy using model predicted tilted surface radiation

Greek

β	Surface slope
ρ_g	Ground reflectance
θ	Angle of incidence (calculated at mid-point of hour)
θ_z	Zenith angle (calculated at mid-point of hour)

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