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ASSESSMENT OF THE ACCURACY OF GENERATED METEOROLOGICAL DATA FOR USE IN SOLAR ENERGY SIMULATION STUDIES

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Abstract—Simulations provide the only practical method for designing solar energy systems. Meteorological data are needed to drive the simulations. However, long-term meteorological data (e.g., 20 years) are not available in most locations so simulations often rely on a reduced set of data or data which have been synthesized with statistical models. Even in locations in which long-term data records exist, the computational requirements of using these data for design purposes is significant so a reduced set of data (e.g., 1 year) is generally used. This study investigates the accuracy of using reduced and synthesized sets of meteorological models for solar applications. The accuracy estimates are made relative to estimates determined with over 20 years of hourly meteorological records.

INTRODUCTION

Solar energy systems are weather-driven. Meteorological data for hourly (or shorter) periods are needed to simulate the performance of these systems. The simulations provide performance estimates which reflect the meteorological data. Ideally, many years of data would be employed in the simulations to properly represent the complex statistical trends inherent in the meteorological variables. Long term weather data (e.g., 20 or more years) are available in some locations. Even with today's technology, however, the computing effort required to simulate solar energy system performance with such a large set of data is significant. If the simulations are to be used repetitively for design purposes, the computing time becomes prohibitive. As a consequence, a single year of "typical" data has often been employed for simulation needs. Typical meteorological year data have been derived from the long term data by Hall *et al.* (1978). Although the typical meteorological year data have been compared to the long-term data, e.g., Menicucci and Fernandez (1988), there has been no systematic study on the accuracy of this smaller set of data as it is used in simulations.

Long-term data are available at only 26 locations in the US. The lack of data has prompted development of a variety of methods to synthesize meteorological data. For example, data at neighboring locations can be interpolated or solar radiation measurements (which are often lacking while other measurements are available) can be inferred from cloud cover or satellite data. Alternatively, weather data can be synthesized based on monthly-average estimates of meteorological variables and statistical distributions of these variables. In this paper, performance estimates of solar energy systems using reduced and synthesized sets of weather data are compared to those obtained using long-term data.

METEOROLOGICAL MODELS

Long term data (LTD)

A meteorological model used for the design of solar devices should represent the average conditions of a location as well as the statistical variations. It should do this on annual, monthly, daily, and even hourly bases. There are only a limited number of years of data from which the average conditions can be ascertained. These records are represented in the SOLMET (1978) long term data (LTD) files. The files are composed of hourly readings of meteorological phenomena, such as global horizontal and direct normal radiation, temperature, wind speed, wind direction, and other measurements for the period between 1952 and 1975. These records currently provide the best available estimates of the long term average conditions and a statistical description of the weather. It is against these records that any model which proposes to represent an annual set of meteorological data must be compared. The main disadvantage of these data is that there are very few (26) available sites.

Typical meteorological year (TMY)

To reduce the computational effort in simulation studies of solar energy applications, reduced data sets, termed typical meteorological year (TMY) files, were developed by Hall *et al.* (1978). The TMY files were originally derived directly from the long-term data. The months that comprise the typical meteorological year are not averages but rather actual data. From the LTD, averages, cross-correlations and distributions were determined for a number of different weather indices. These statistical variables were determined for each month. A hierarchy of criteria was established to select 1 month from the 23 years of data which most accurately represented the LTD. The specified criteria cannot be completely met since no actual month will perfectly match the LTD conditions. This process was performed for the 26 locations in the US for which data were available. Data for many other locations, called ERSATZ data (Menicucci and Fernandez, 1988) were generated from the known data of other meteorological quantities such as cloud cover and sunshine hours. Additional data of this type are being prepared for the National Solar Radiation Data Base (1992).

Hourly weather generator (GEN)

A method for generating hourly solar radiation and ambient temperature data was developed by Knight *et al.* (1991). This method has been incorporated into the TRNSYS (Klein *et al.*, 1990) simulation program as the Type 54 weather generator (GEN). The weather generator algorithms require as input, the monthly average daily global horizontal radiation, $\bar{H}$, and ambient temperature, $\bar{T}$, to produce a year of hourly meteorological data. A major advantage of the weather generator is that, with this model, simulations could be run for any location in which monthly-average solar radiation and ambient temperature are known. A short summary of the methodology employed in this model follows.

The monthly daily average radiation value, $\bar{H}$, is used to compute the monthly average daily clearness index, $\bar{K}_T$.

$$\bar{K}_T = \bar{H}/\bar{H}_0 \quad (1)$$

where $\bar{H}_0$ is the monthly average daily extraterrestrial radiation. $\bar{K}_T$ is used to select a cumulative frequency distribution of daily clearness indices, K_T, using the cumulative frequency distributions originally proposed by Liu and Jordan (1960) which have the form shown in Fig. 1. Analytical expressions for these generalized frequency distributions have been proposed by Bendt *et al.* (1981) and by Hollands and Huget (1983). The Hollands and Huget expression is a fit to Liu and Jordan's original distributions whereas the distributions of Bendt *et al.* are based on approximately 20 years of daily radiation at 90 US locations. The Liu and Jordan, Bendt *et al.*, and Hollands and Huget distributions are quite similar and they are in good agreement with the data from eight temperate near sea-level locations compiled by Olseth and Skartveit (1984). However, Saunier *et al.* (1987) have noted that these distributions are not universal and that they are particularly poor in representing the distributions in tropical and subtropical locations. Saunier *et al.* (1987) and Gordon and Reddy (1988) have proposed alternative distribution functions.

The Bendt *et al.* (1981) cumulative distribution function has been used to generate the radiation data considered in this study. However, any distribution function can be used in this radiation generation method. The distribution function should be selected to best represent the climate of interest.

GEN determines daily values of K_T from the cumulative clearness index frequency distribution. These

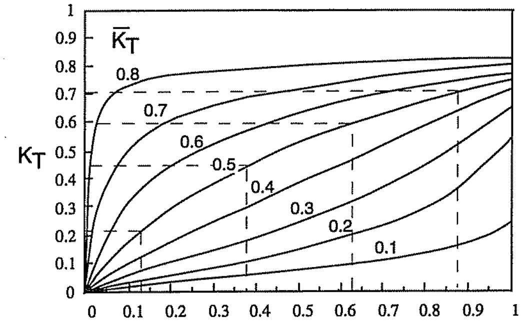


Fig. 1. Cumulative distribution of clearness indices as a function of $\bar{K}_T$.

clearness indices are then ordered so that their lag-one autocorrelation is approximately 0.30. This value was chosen based on analyses of long-term data which indicate that the lag-one autocorrelation of daily radiation ranges between 0.15 and 0.35 in many locations independent of climate type, as found by Klein and Beckman (1987).

Once the daily clearness indices are known, the mean clearness index for each hour is determined by the product of the daily clearness index and the ratio r_t/r_d where r_t is the average ratio of hourly to daily total radiation and r_d is the average ratio of hourly to daily extraterrestrial radiation as shown in Duffie and Beckman (1991).

$$r_t = \frac{I}{H} = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \quad (2)$$

$$a = 0.409 + 0.5016\sin(\omega_s - 60°) \quad (3)$$

$$b = 0.6609 + 0.4767\sin(\omega_s - 60°) \quad (4)$$

$$r_d = \frac{I_o}{H_o} = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \quad (5)$$

Figure 2 shows a comparison of the r_t (hourly/daily radiation) ratios determined from the long-term data, the typical mean year data and eqns (2–4) for Madison, WI. The correlation appears to provide excellent agreement with the data. The hourly clearness indices, k_t, are estimated from the mean values by a stochastic model developed by Graham (1985). To ensure that the hourly radiation values add up to the target daily value, the hourly clearness indices are corrected such that

$$\sum^{\text{hours}} k_t I = K_T H \quad (6)$$

A similar model is used to generate hourly ambient temperature data using distribution functions developed by Erbs *et al.* (1983). Given the monthly-average

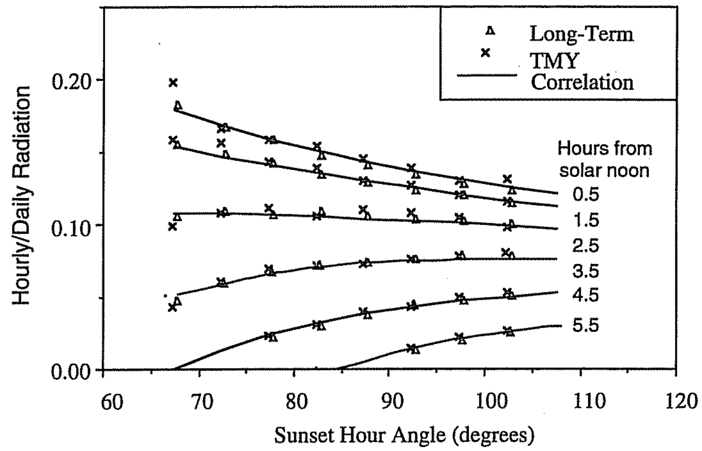


Fig. 2. Comparison of hourly/daily radiation ratios for Madison, WI determined using LTD, TMY, and eqns (2–4).

ambient temperature, the average daily temperatures for each day in the month are determined from the cumulative distribution function. The average hourly temperatures are determined as a function of the daily average temperature using the diurnal temperature correlation where the amplitude depends on the daily K_T value. The stochastic variation of the hourly temperature about its mean value is modelled with a second-order autoregressive stochastic correlation by Knight *et al.* (1991). The TRNSYS Type 54 weather generator thus produces a month of hourly radiation values and temperatures. Other correlations included in the model determine wind velocity and relative humidity. However, these statistics were not investigated here.

Compressed weather generation (COM)

"Compressed" weather attempts to represent the important statistics of an entire month of days with N selected days where N is less than the actual number of days in the month. The incentive for using compressed weather is to reduce the computational effort required to do simulations. Two questions arise concerning the generation of compressed weather data for SDHW simulations: (a) How many days are required and in which order should the days be arranged to accurately represent a month? and, (b) is the stochastic component in radiation and ambient temperature data important? In the formulation of compressed weather data used in this investigation, N is 4. The importance of the stochastic component is addressed below.

Hollands *et al.* (1989) investigated the effect of the stochastic temperature component on the performance of active solar hot water systems. They performed detailed simulations over a range of system parameters, locations, and hot water load profiles. One set of simulations used TMY temperature data, whereas the other set used a deterministic profile. Systems were found to perform better when subjected to the deterministic temperature profile rather than the TMY profile in all cases. However, the differences were small, with maximum relative errors in yearly solar fractions between the two sets of simulation being on the order of +1%. Hollands *et al.* also performed a third set of simulations using a constant ambient temperature equal to the monthly average daily temperature. The maximum relative error in solar fraction between simulations using the constant and TMY ambient temperature was +5%. Hollands concluded that neglecting the stochastic temperature component is acceptable for standard SDHW system designs.

A process similar to that used by Hollands *et al.* was used by Schaefer (1991) to investigate the importance of the stochastic radiation component on SDHW system performance. Simulations were performed using actual and "smoothed" TMY radiation data in which the stochastic component has been removed. Smoothed radiation data are necessarily symmetric about solar noon. Schaefer simulated solar water heating systems with both hourly TMY and smoothed radiation data over a range of parameter variables for January and July in Albuquerque, NM; Madison, WI; and Seattle, WA. He concluded that neglecting the stochastic components of the hourly variations in both solar radiation and ambient temperature resulted in an average error of ±1% with a maximum of ±3%.

The following steps are taken in generating the 4 days of compressed weather data. The monthly-average daily horizontal solar radiation and ambient temperature are selected for each month in the location of interest. $\bar{K}_T$ is determined from eqn (1). Four days, each represented by a daily K_T value, are then selected from the cumulative clearness index distribution such that they have an average of $\bar{K}_T$. The K_T values represent fractional times of 0.125, 0.375, 0.625, and 0.875, as shown by the dotted lines in Fig. 1. Using the Bendt *et al.* (1981) distribution function, the average of the four values of K_T corresponding to these four fractional times are within 0.01 of the target value of $\bar{K}_T$ for $\bar{K}_T$ between 0.3 and 0.7. The 4 days are arranged in sequence 1–3–2–4 where 1 and 4 refer to the K_T values at fraction times of 0.125 and 0.875, respectively. The hourly values of horizontal total radiation, I, for each daily K_T value are determined using eqn (2). The ratio of hourly to daily diffuse radiation is approximated as the ratio of hourly to daily extraterrestrial radiation given by eqn (5).

The hourly radiation values are corrected such that their sums are exactly equal to the known monthly-average values. The hourly ambient temperatures are assumed to be same for each day with a diurnal variation given by the Erbs *et al.* (1983). The stochastic component is ignored.

Average day (AVG)

The average day model (AVG) attempts to represent a month with a single average day. The radiation and ambient temperature on this day are the monthly average daily horizontal radiation and ambient temperature. Hourly values of total and diffuse radiation are determined from eqns (2) and (5). Hourly ambient temperatures are estimated using the Erbs *et al.* (1983) diurnal temperature model. The meteorological data for the average day of the month are then used each day of the month. Every day is symmetrical about noon and identical to every other day in that month in terms of horizontal radiation and ambient temperature so that this one day completely represents the month. In practice, simulations are repeated for 2 or 3 days until steady-periodic results are obtained. This model was investigated to determine the error in estimated performance resulting from using a single average day to represent the month. The error should provide an upper bound on the error associated with using generated weather data.

MODEL ANALYSIS

The different meteorological models were compared to the long-term data on the basis of a number of criteria. Monthly-average daily tilted surface radiation, solar radiation utilizability, cumulative frequency distributions, and simulated performance of solar domestic water heating systems were all compared in calculations for Madison, WI; New York, NY; Seattle, WA; Albuquerque, NM; Fort Worth, TX; and Miami, FL. The calculations of the weather variables and simulated system performance were done using TRNSYS. The Perez *et al.* (1988) anisotropic sky model was used to estimate diffuse radiation. A constant ground reflectance of 0.2 was assumed in all models.

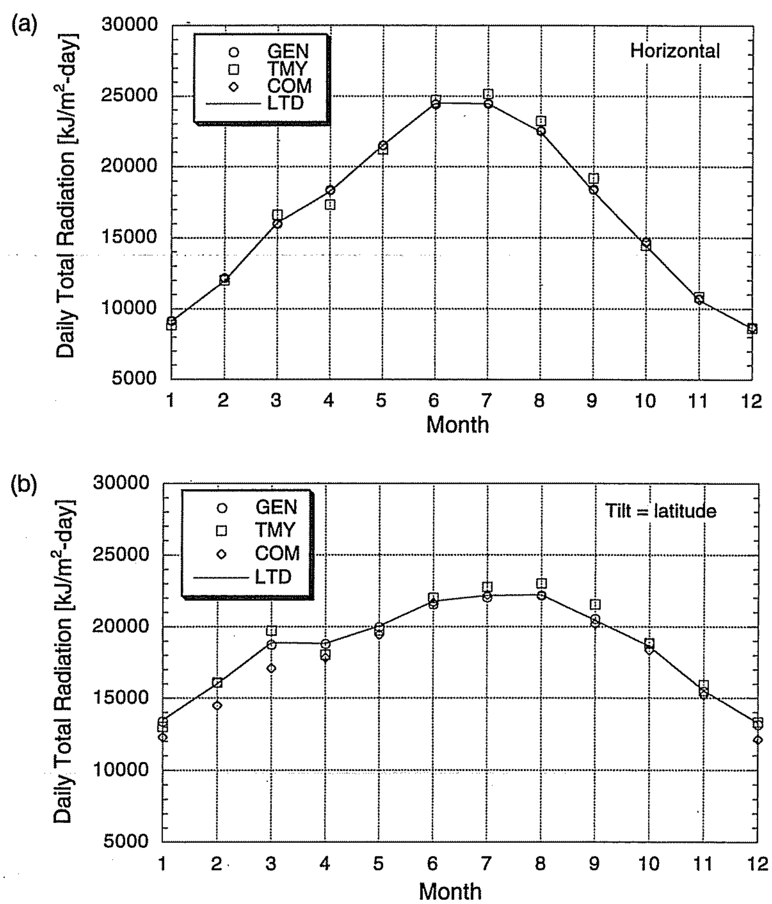


Fig. 3. (a) Average daily horizontal surface radiation, Fort Worth, TX; (b) Average daily tilted surface radiation, Fort Worth, TX.

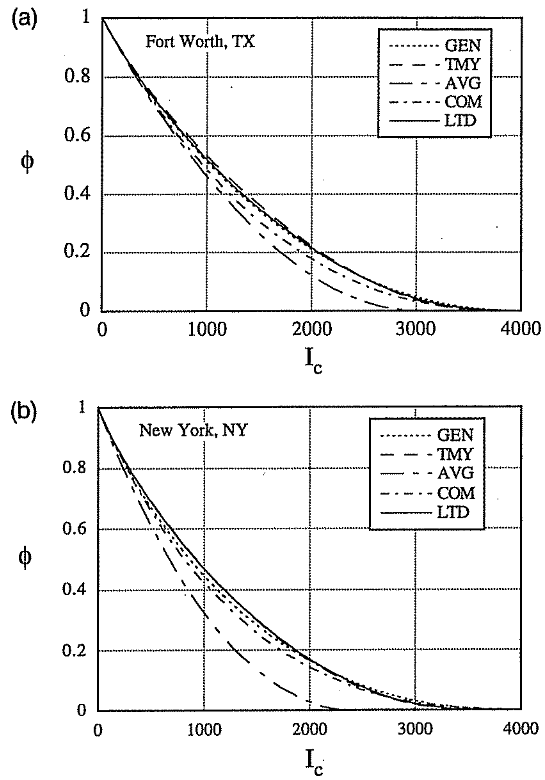


Fig. 4. (a) Annual utilizability, Fort Worth, TX; (b) Annual utilizability, New York, NY.

Average radiation

The errors in calculated average daily horizontal radiation were quite small for all models as seen in Fig. 3a for Fort Worth, TX. This agreement is expected since all models use the same monthly-average daily radiation as input. However, differences appear for tilted radiation (at a tilt equal to latitude) as seen in Fig. 3b. While GEN continues to correspond well to the LTD, TMY and COM begin to show marked differences. COM in particular seems to exhibit a general trend for all locations. It tends to underpredict in the winter months and then overpredict in summer months. Nevertheless, it does a good job of representing the long term behavior.

Utilizability

Most solar-driven systems do not respond linearly to average solar radiation. As a result, the distribution of radiation around the average, as well as the average itself, is important. This effect can be quantified by a utilizability analysis. Utilizability is defined as the fraction of energy above a given critical level. Applications for solar radiation utilizability are presented by Klein and Beckman (1984).

Klein (1978) defined daily utilizability as

$$\bar{\phi} = \frac{\sum_{\text{days}} \sum_{\text{hours}} (I_T - I_{TC})^+}{\bar{H}_T N} \tag{7}$$

where I_T is an hourly value of tilted radiation, I_{TC} is the critical value of radiation, and $\bar{H}_T$ is the monthly-average daily tilted radiation. Since N is the number of days in the month, $\bar{H}_T N$ is the total tilted radiation for the month.

The utilizability analysis was performed on both an annual as well as a monthly basis as reported more fully by Gansler (1993). One hundred critical levels ranging from 0 to 4000 kJ/m^2-hr were used. The AVG estimates of utilizability were poor for all locations as apparent in the results for Fort Worth and New York in Figs. 4a and 4b. AVG will always perform poorly since it does not represent the daily radiation distribution except in climates such as Albuquerque, NM where every day is nearly the average day. The utilizability obtained from the COM model slightly underestimates utilizability for most critical levels compared to the LTD whereas the TMY and GEN models compare well with the long-term data to the point that they cannot easily be distinguished in Figs. 4a and 4b. The slightly different shapes of these utilizability curves and the fact that they cross indicate that they represent different radiation distributions. Figure 5 shows the bias error for the 12 monthly utilizability curves for New York. The bias error is the difference in the utilizability calculated by the meteorological model compared to

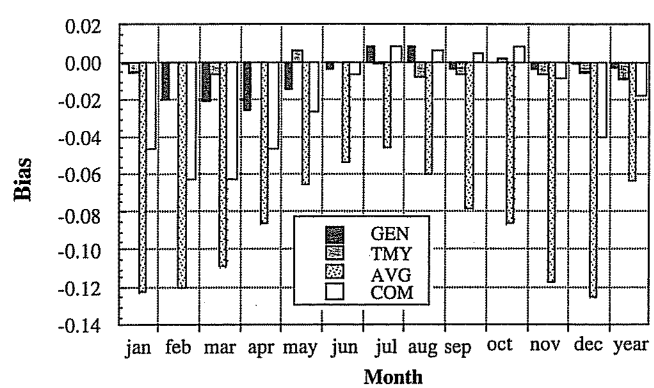
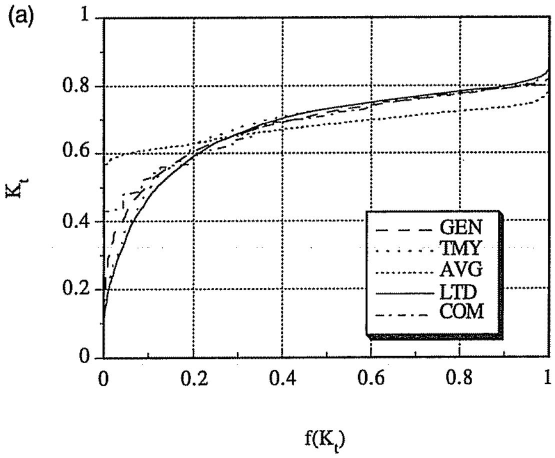


Fig. 5. Average utilizability bias, New York City.



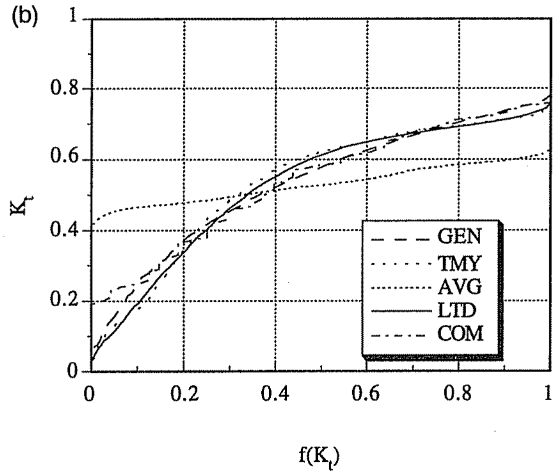


Fig. 6. (a) Annual cumulative frequency distributions of daily clearness indices, Albuquerque, NM; (b) Annual cumulative frequency distributions of daily clearness indices, Fort Worth, TX.

that determined from the long-term data. The trend for all locations is that the models underpredict in the winter months whereas they more closely match in the summer months.

Cumulative frequency distribution (CFD)

Annual cumulative frequency distributions (CFD) of daily clearness indices were generated for the six locations. The CFD as a function of K_T for Albuquerque and Fort Worth in Fig. 6 shows that both GEN and TMY fall very close to the long term distribution. In fact, for all locations, TMY reproduces the long term CFD almost exactly. GEN does well, but not quite as well as TMY. Once again, the AVG model fares quite poorly because the radiation distribution is not considered. It seems that TMY more accurately reproduces the behavior of the long term curve while GEN conforms more to a Bendt distribution, as it was designed to do.

CRITICISM OF GENERATED WEATHER

Collares-Pereira and Aguiar (1992) claim that the method of generating hourly clearness indices, as done in GEN and COM, has the deficiency of mixing days and hours of differing characteristics. Instead, they propose that the hourly clearness indices, k_t, should be grouped by solar altitude angle, α, and daily clearness index, K_T. They performed such an analysis with a set of data from six locations in Europe and Africa. Probability distributions were generated on the basis of days of a given K_T. For each k_t, the data were grouped by the hourly altitude angle α. They found that, for a low K_T, the distributions of k_t/k_{tm} are essentially the same for all solar altitude angle values in that there is a great deal of variance. For high K_T values, however, there was a marked peak at $k_t/k_{tm} = 1$ and that this peak increased for higher α (lower airmass).

The long term data were employed to see if airmass effects are important in US data. The data for the six locations were processed in order to find k_t, θ_z, and K_T. The data were separated by K_T and grouped by $\cos(\theta_z)$. The values of k_t/k_{tm} were placed into bins of width 0.1 ranging from 0.0 to 3.0. These bins were then normalized so that the sum of their values was 100. At $0.25 < K_T \leq 0.30$, the probability plots are similar to that in Fig. 7 for Albuquerque. In addition, there seems to be a large variation about the value $k_t/k_{tm} = 1$. At $0.65 < K_T \leq 0.70$, the distributions have a sizable peak around $k_t/k_{tm} = 1$ as evident in Fig. 8. Furthermore, the magnitude of the peak increases as $\cos(\theta_z)$ increases and as K_T increases suggesting that on clear days, hours are more likely to be at k_{tm} and the likelihood is stronger for the central hours for the day. On cloudier days, there is more of a distribution around k_{tm} and the likelihood is independent of time

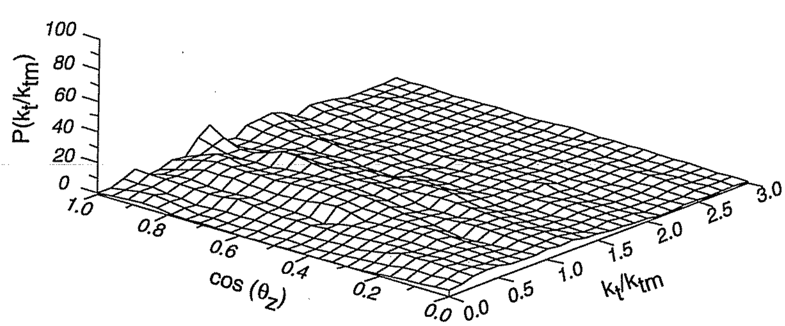


Fig. 7. Probability plot, $0.25 < K_T \leq 0.30$ for Albuquerque, NM.

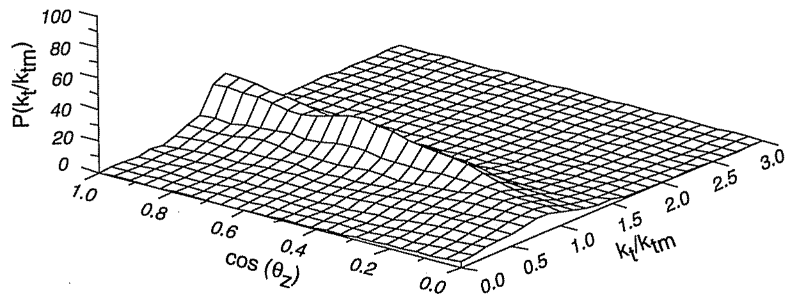


Fig. 8. Probability plot, $0.65 < K_T \leq 0.70$ for Albuquerque, NM.

of day. The GEN and COM meteorological models do not correctly reproduce this behavior.

SOLAR WATER HEATING SYSTEM SIMULATIONS

A simulation model of a forced-circulation solar domestic hot water (SDHW) system was constructed using TRNSYS (Klein *et al.* 1990) to assess the effect of differences in the meteorological models on the estimated long-term performance of a solar system. The SDHW system used flat-plate collectors and a 300 l water storage tank. The system load was 300 l per day. Figure 9 compares the simulation results for the different radiation models in six locations. The collector energy loss factor, $F_R U_L$, was assumed to be 4.17 W/m^2 K, representative of double-glazing or single-glazing with a selective surface. The collector size was selected in each location to meet approximately 50% of the annual water heating load. The flow rate per unit collector area and the size of the storage tank were held constant in all simulations. The differences between the predictions of the meteorological models are about 5%, but there are systematic trends. The AVG model consistently gives lower solar fractions than the other models. However, all of the models compare quite favorably to the long term results.

When a higher loss collector is used in the system ($F_R U_L$ = 8.33 W/m^2 K) the differences among the models are accentuated as is evident in Fig. 10. For some locations, the model choice does not matter much. The decrease in solar fraction from the initial values of 50% is the same for all of the models. However, for others, the differences become much more noticeable.

Additional simulations were performed with a solar fraction target of 75%. Figures 11 and 12 show that the solar fractions calculated using the models are close to those using long term data, even when a higher loss collector was used. Only the AVG model produces inaccurate estimates.

CONCLUSIONS

No model will be able to reproduce the long term behavior of the multitude of meteorological phenomena and all of their interrelations. The weather generator developed by Knight *et al.* (1991) and the 4-day month representation investigated by Schaefer (1991) are attempts to reduce the computational aspects of solar energy systems without sacrificing accuracy. Both of these meteorological models were found to produce meteorological statistics (such as monthly solar radiation on an inclined surface and monthly utilizability) and simulated performance of solar domestic hot water systems which compare well with results obtained from long-term hourly records.

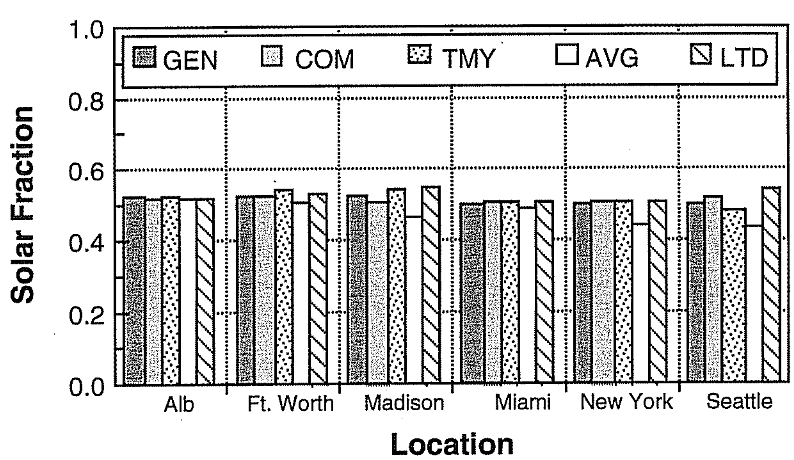


Fig. 9. Calculated annual solar fractions with $F_R U_L$ = 4.17 W/m^2 K.

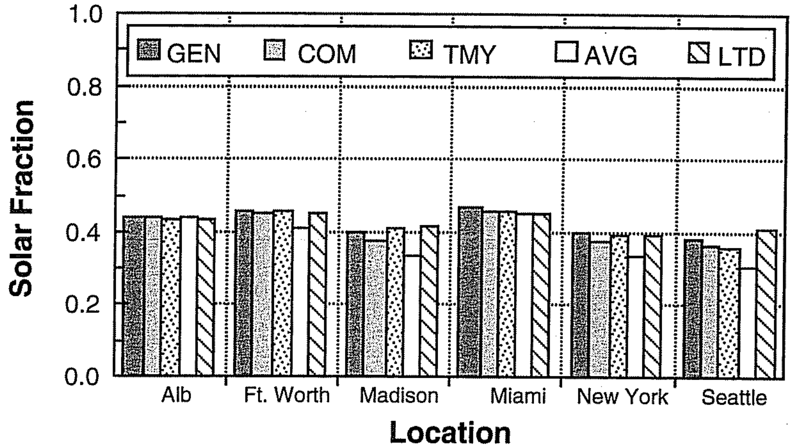


Fig. 10. Calculated annual solar fractions with $F_R U_L = 8.33$ W/m^2 K.

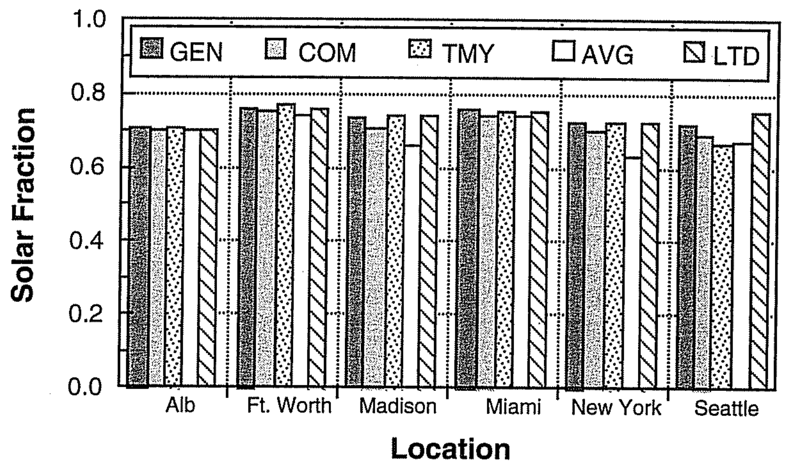


Fig. 11. Calculated solar fraction, $F_R U_L = 4.17$ W/m^2 K.

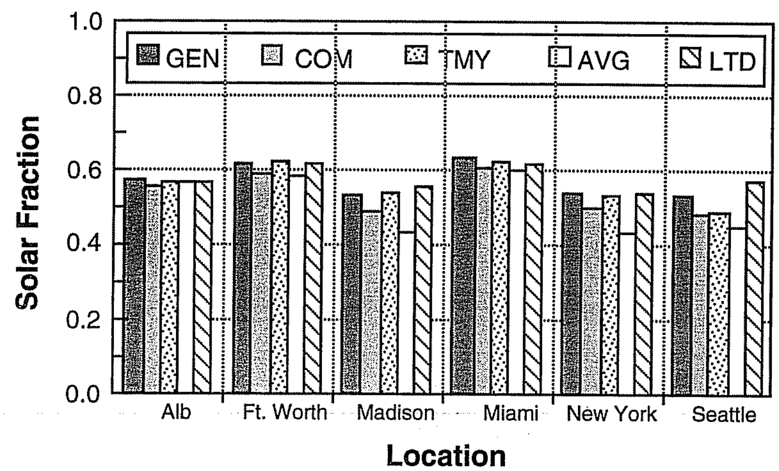


Fig. 12. Calculated solar fraction, $F_R U_L = 8.33$ W/m^2 K.

In some cases, these models compare more closely to the long-term data than the results obtained using the typical meteorological year. The 1-day model, however, did not provide useful results, except for most months in Albuquerque in which the hourly weather can be well-approximated with a monthly-average model. These results indicate that synthesized weather data can be reliably used in simulations of some solar energy systems thereby allowing simulations to be used as a design tool in locations for which hourly data records do not exist.

NOMENCLATURE

CFD Cumulative Frequency Distribution
COM Compressed (4-day) weather generator
GEN Weather generator
H Daily horizontal radiation
H_o Daily extraterrestrial horizontal radiation
H_t Daily radiation on a tilted surface
I Hourly horizontal radiation
I_o Hourly extraterrestrial horizontal radiation
I_t Hourly radiation on a tilted surface
k_t Hourly clearness index
k_{tm} Mean hourly clearness index
K_T Daily clearness index
$\bar{K}_T$ Monthly average daily clearness index
LTD Long term data
T Daily ambient temperature
T_h Hourly ambient temperature
$\bar{T}$ Monthly average daily ambient temperature
$\bar{T}_h$ Monthly average hourly ambient temperature
TMY Typical meteorological year
α Altitude angle
ϕ Utilizability
θ_z Solar zenith angle
ω Hour angle
ω_s Sunset hour angle

REFERENCES

P. Bendt, M. Collares-Pereira, and A. Rabl, The frequency distribution of daily insolation values, *Solar Energy* **27** (1), 1-5 (1981).

Collares-Pereira and Aguiar, Statistical properties of hourly global radiation, *Solar Energy* **48** (3), 157-167 (1992).

J. A. Duffie and W. A. Beckman, *Solar engineering of thermal processes*, Wiley, New York (1991).

D. G. Erbs, S. A. Klein, and W. A. Beckman, Estimation of degree-days and ambient temperature bin data from monthly-average temperatures, *ASHRAE Journal*, June, (1983).

J. M. Gordon and T. A. Reddy, Time series analysis of daily horizontal solar radiation, *Solar Energy* **41** (3), 215-226 (1988).

R. A. Gansler, Assessment of generated meteorological data for use in solar energy simulations, M.S. Thesis, Mechanical Engineering Department, University of Wisconsin-Madison, Madison, Wisconsin (1993).

V. A. Graham, Stochastic synthesis of solar atmospheric transmittance, Ph.D. Thesis, Mechanical Engineering Department, University of Waterloo, Waterloo, Ontario, Canada (1985).

I. J. Hall, R. R. Prairie, H. E. Anderson, and E. C. Boes, Generation of a typical meteorological year, *Proceedings of* 1978 *Annual Meeting*, American Section of ISES, Denver **2** (2), 669 (1978).

K. G. T. Hollands and R. G. Huget, A probability density function for the clearness index, with applications, *Solar Energy* **30** (3), 195-209 (1983).

K. G. T. Hollands, L. J. D'Andrea, and I. D. Morrison, Effect of random fluctuations in ambient air temperature on solar system performance, *Solar Energy* **42**, 335-338 (1989).

K. M. Knight, S. A. Klein, and J. A. Duffie, A methodology for the synthesis of hourly weather data, *Solar Energy* **46** (2), 109-120 (1991).

S. A. Klein, Calculations of flat-plate collector utilizability, *Solar Energy* **21**, 393 (1978).

S. A. Klein, *et al.* TRNSYS 13.1 user's manual, Engineering Experiment Station Report 38-13, Solar Energy Laboratory, University of Wisconsin-Madison (1990).

S. A. Klein and W. A. Beckman, Review of solar radiation utilizability, *ASME Journal of Solar Energy Engineering* **106** (4), 393-402 (1984).

S. A. Klein and W. A. Beckman, Loss of load probabilities for stand-alone photovoltaic systems, *Solar Energy* **39** (6) (1987).

B. Y. H. Liu and R. C. Jordan, The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation, *Solar Energy* **4** (3) (1960).

D. Menicucci and J. Fernandez, A comparison of typical meteorological year solar radiation information with the SOLMET data base, Sandia National Laboratory Report SAND87-2379 (1988).

National Solar Radiation Data Base, *User's manual*, Vol. 1, National Climatic Data Center, Asheville, NC (1992).

J. A. Olseth and A. Skartveit, A probability density function for daily insolation within the temperate storm belts, *Solar Energy* **33** (6), 533-542 (1984).

R. Perez, *et al.*, The development and verification of the Perez diffuse radiation model, Sandia National Laboratories Contractor Report SAND88-7030 (1988).

G. Y. Saunier, T. A. Reddy, and S. Kumar, A monthly probability distribution of daily global irradiation values appropriate for both tropical and temperature locations, *Solar Energy* **38** (3), 169-177 (1987).

P. Schaefer, Modeling of solar domestic hot water systems, M.S. Thesis, Mechanical Engineering Department, University of Wisconsin-Madison, Madison, Wisconsin (1991).

SOLMET, *Hourly solar radiation surface meteorological observations*, Vol. 1 and 2 US National Climactic Center, Asheville, NC (1978).