GRAPHICAL ANALYSIS OF REAL SKIES WITH THE CLEAR DAY INDEX: USING PENN STATE SURFRAD DATA

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ABSTRACT

Graphical methods are explored as an educational tool to convey the complimentary nature of clear sky models, clearness indices, and meteorological data. The hourly clearness index (k_T) and the hourly clear sky index (k_c) can be used in energy simulations to convey anisotropic conditions of shortwave irradiation on oriented surfaces, used for long-term performance of solar energy conversion systems. The hourly clear sky index is the ratio of a measured global horizontal irradiation (I) relative to an estimated clear sky condition, I_c (MJ/m^2), in contrast with the traditional clearness index calculated under AM0 irradiation conditions, I_0. Measured data were collected from the SURFRAD monitoring station near Penn State. Clear sky estimation used the Bird Clear Sky Model (National Renewable Energy Laboratory) for global horizontal irradiation (GHI) and direct normal (DNI), as well as components of beam, and hemispherical diffuse irradiation. Days in January and July were assessed for State College, PA. Our graphical approach explores the combined plot of the measured and clear sky components. A stronger understanding is conveyed in the graphical approach for the relationships between components of solar irradiation and the role of air chemistry, clouds, and ground conditions.

1. INTRODUCTION

There is value in visualizing both real measured data or irradiance from a top level monitoring station, and the component breakdown of irradiance estimated for an otherwise clear sky day. The intent of this study has been to integrate undergraduate learning into the process of data visualization, by bringing students and faculty together to discuss the results of the data processing that ultimately leads to component based models of the solar resource. There is a gap in communication for most introductory students of solar resource assessment regarding the flow of information from ground-station average irradiance measurements upon a horizontal surface, to component models of irradiance on a horizontal surface, and finally integration of components upon a specially tilted collecting surface.

As displayed in Figure 1, the processing of horizontal irradiance data from ground stations into useful irradiation data for a tilted surface calls for multiple steps, and there are additionally multiple avenues to access the meteorological data at various points in the data process. The young professional will often experience challenges in understanding the connectivity between a summary value such as an hourly clearness index (k_T) and the predicted irradiation upon a photovoltaic array or solar hot water panel that has a specific non-horizontal orientation.

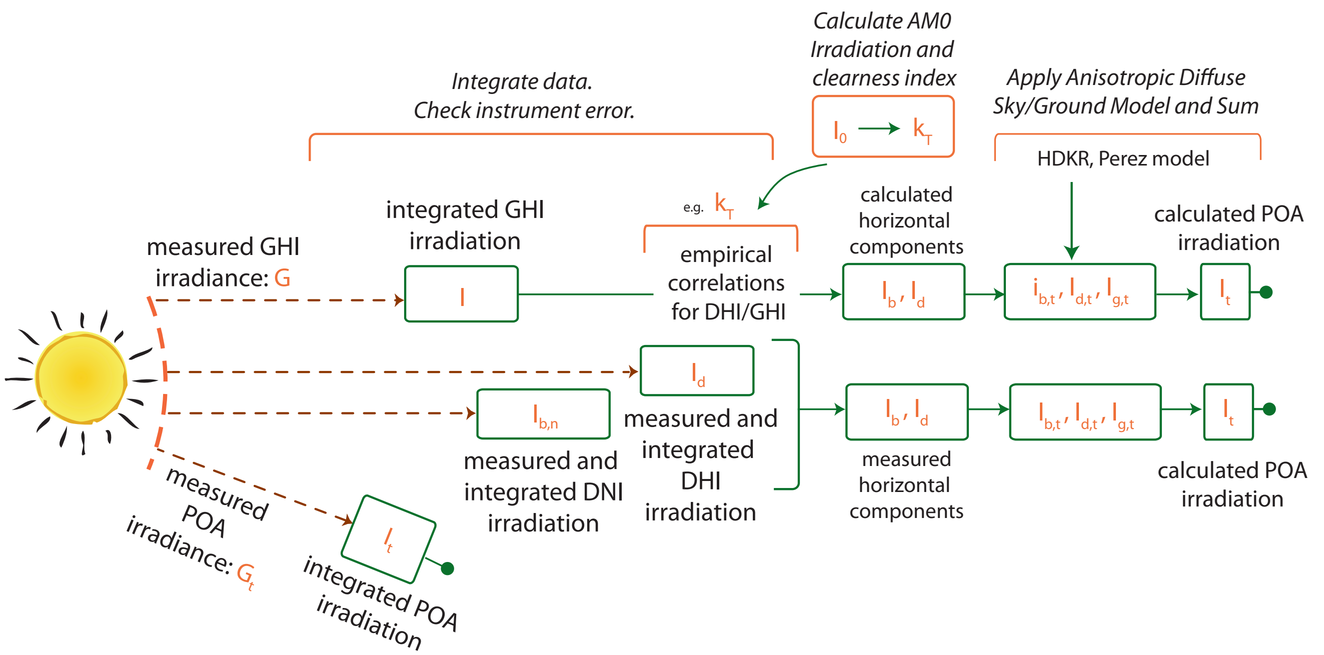

Fig. 1: Protocols for processing irradiance data from GHI into hourly irradiation data upon a tilted surface (I_t). Hourly data

Furthermore, students and young professionals can be challenged to understand the complimentary value of a clear sky component model for a horizontal surface, connected with the measured data of GHI, DHI, and DNI from a terrestrial solar research station. We pose that by integrating the role of measured data with summary metrics such as the clearness and clear sky indices, and overlaying that information with clear sky component estimations, a rich learning environment is exposed for data exploration, higher understanding of meteorolgoical and ground conditions, and a stronger skill in model fitting with incomplete information on site.

In this paper we chose to visualize the net solar irradiation in summer and winter months for central Pennsylvania, a mid-Atlantic climate regime often characterized qualitatively as being "cloudy". Our observations were based on the data from the Surface Radiation Budget Network (SURFRAD) data station just outside of State College, PA.[1] The compilation of the data and construction of a visual comparison was performed for educational benefit, to compare the hourly summary values of the *clear sky index* and the *clearness index* with the real measured data and predicted clear sky conditions.[2,3]

SURFRAD operates at six different geographic locations in the United States including one outside of University Park, Pennsylvania. The stations monitor several metrics of climatological data, including upwelling and downwelling shortwave and longwave irradiance as primary measurements. Ancillary observations include direct and diffuse shortwave, photosynthetically active radiation (PAR), UVB, and additional meteorological parameters.

The hourly clearness index (k_T, Eq. 1) is a ratio that can be used in the process of evaluating long-term performance of a solar energy conversion system, such as photovoltaics, solar thermal systems, or the built environment. The ratio reflects the measured global horizontal solar radiation at a site relative to an ideal calculated horizontal irradiation for air mass 0 (AM0, extraterrestrial) for the equivalent latitude and time of the locale under study. The hourly clear sky index (k_c, Eq. 2) applies the estimated values of clear sky irradiation. The hourly clearness index is a core step in the process to estimate the various components of light incident upon a tilted or horizontal surface, used to approximate the diffuse contributions of light from the sky dome upon a surface using the same measurements [2,3].

Finally, there are a number of modeling tools to estimate the clear sky condition, and each requires a significant number of parametric inputs related to atmospheric concentrations of ozone, water vapor, O_2, N_2, CO_2, and aerosols, in addition to physical conditions of pressure and ground reflectance (albedo). The Bird Clear Sky Model has been an established algorithm from the US DOE National Renewable Energy Laboratory that estimates clear sky direct beam, hemispherical diffuse, and total hemispherical solar radiation for the horizontal plane of incidence.[4] The model is presently available in spreadsheet form, which proved to be an excellent starting point for undergraduate research.

2. METHODS

Three days were chosen in January (3, 10, 15) and three days in July (6, 15, 31) for graphical analysis. These days were selected in an effort to depict typical summer and winter days, both "clear" and overcast. In order to calculate the hourly clearness index and the hourly clear sky index, measured data was collected from the SURFRAD operating station located approximately 15 km southwest of State College, PA (Penn State University). The primary data set from the Penn State SURFRAD monitoring station collects irradiation values at three-minute intervals. To arrive at hourly energy density values (J/m^2) from measured one-minute primary data, the data was integrated with the trapezoidal integration method.

$$k_t = \frac{I}{I_0} \tag{1}$$

$$k_c = \frac{I}{I_c} \tag{2}$$

The algorithm for the hourly clear sky index is seen in Equation 2, while the hourly clearness index is shown in Equation 1. Data for extraterrestrial (AM0, air mass zero) irradiation were calculated in Scilab using standard algorithms to estimate hourly irradiation from spherical trigonometry seen in Equation 3.[5]

$$I_0 = \frac{12 \cdot 3600}{\pi} \cdot G_{0,n} \times \left[\frac{\pi}{180}(\omega_2 - \omega_1) \sin\phi \sin\delta + \cos\phi \cos\delta (\sin\omega_2 - \sin\omega_1) \right] \tag{3}$$

where ω is the hour angle for hourly endpoints 1 (beginning) and 2 (end), ϕ the latitude of of the collection station, δ the declination for the day of interest, and $G_{0,n}$ the normal irradiance at AM0.

The estimated hourly values of clear sky irradiation (I_c) were complied using the Bird Clear Sky Model. The latitude and longitude of State College, PA were know to be 40.7° N and 77.9° W.[1] The Time Zone is EST (UTC-5 hours) and the albedo was adjusted based on the seasons (0.8 for January and 0.2 for July). The higher value for reflectance was assumed due to the typical snow cover during the winter in State College. The other parameters used Bird Clear Sky default settings.[4]

Parameters for Bird Model

Latitude	Longitude
Time Zone	Pressure
Ozone Thickness	Water Vapor
Aerosol Optical Depth @500 nm	Aerosol Optical Depth @380 nm
Broadband Optical depth (τ)	Forward Scattering
Albedo (Ground Reflectance)	

When creating a graphical representations for comparison, several adjustments had to me made in order to align the two plots. In July, two hours were added to each day to avoid day truncation at the end of each day. Also, the albedo (ground reflectance) was modified during the January dates to account for snow for the Winter.

The hourly clearness index (k_T) is a ratio of measured irradiation to the extraterrestrial irradiation calculated (AM0). The hourly clear sky index uses calculated values of clear sky irradiation for that day. To find the measured value for each ratio, the integral was taken under the SURFRAD data. In the hourly clear sky index, the calculated value was found by integrating under the GHI value curve. Also, the hourly clear sky index (k_c) is dependent on clouds, making it a potentially more informative metric than the hourly clearness index (k_T) which does not separate clouds from the contributing clear sky. The cloud index can therefore be calculated from the clear hour index by subtracting the k_c from 1.[6]

Below are the hours that were studied:

Hours studied for each day	
January 3, 2007	9:00 to 10:00am 1:00pm to 2:00pm
January 10, 2007	9:00 to 10:00am 1:00pm to 2:00pm
January 15, 2007	9:00 to 10:00am 1:00pm to 2:00pm
July 6, 2007	7:00am to 8:00am 1:00pm to 2:00pm
July 15, 2007*	7:00am to 8:00am 1:00pm to 2:00pm *12:30pm to 1:30pm* *1:30pm to 2:30pm*
July 31, 2007	7:00am to 8:00am 1:00pm to 2:00pm

*The reasoning behind analyzing 4 hour intervals on July 15 is due to the abnormal conditions observed on that day. This day, graphically shown as Figure 6, had an apparent storm pass through the 12:30pm to 1:30 hour. The next hour, 1:30pm to 2:30pm, was analyzed to show a comparison of a sunny hour to an hour with a high cloud index.

3. RESULTS & DISCUSSION

In reviewing the resulting data we observe that a graphical representation paired with the values of the hourly clearness index and the hourly clear sky index enables one to interpret meteorological data and draw conclusions on the significance of these educational tools. We explored various approximations of the components of light incident upon horizontal surfaces by selecting specific hours on different days for both the winter and summer seasons. It is observed through graphical representation and the values of the indices that there are qualitative and quantitative differences between both the different ratios and the two climate regimes.

3.1 January 3, 2007

Figure 2 shows January 3, 2007, a very clear day with more direct irradiance than is predicted by the Bird model. This is due to the underlying assumptions about albedo, aerosol optical depth, and other atmospheric properties.

January 7, 2007	
Hour	k_c and k_t
9:00 to 10:00am	k_t=0.59 k_c=0.96
1:00pm to 2:00pm	k_t=0.76 k_c=1.00

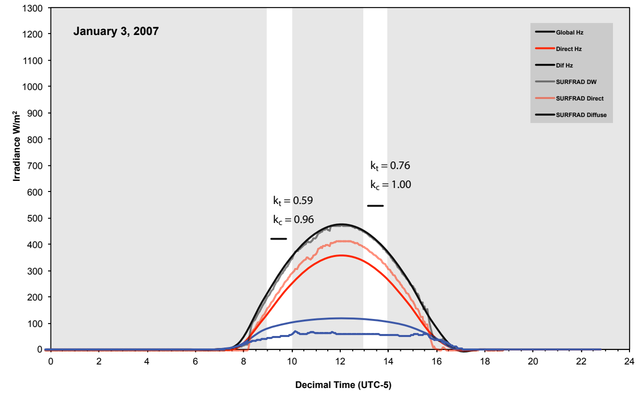

Fig. 2: Bird Clear Sky Model compared against measured 3-minute average irradiance data from the Penn State SURFRAD data collection site.

3.2 January 10, 2007

Figure 3 shows January 10, 2007, a day with scattered clouds. The SURFRAD data dips down to the Bird model diffuse curve periodically, representing periods of mostly diffuse light where the sun is obscured by clouds.

January 10, 2007	
Hour	k_c and k_t
9:00 to 10:00am	k_t=0.50 k_c=0.85
1:00pm to 2:00pm	k_t=0.37 k_c=0.48

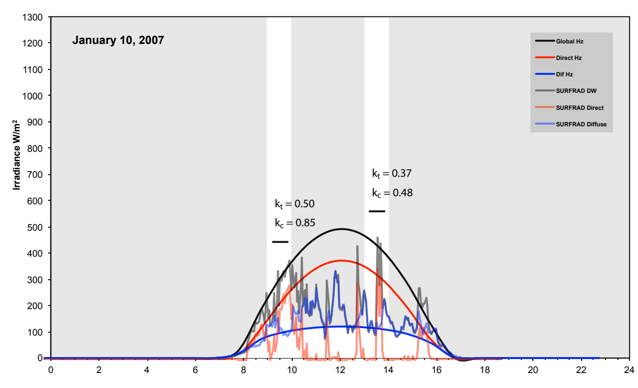

Fig. 3: BIRD Clear Sky Model compared against measured 3-minute average irradiance data from the Penn State SURFRAD data collection site.

3.3 January 15, 2007

Figure 4 shows January 15, 2007, an extremely cloudy day. The SURFRAD curve of the global horizontal irradiance does not reach the diffuse Bird model curve at all. The cloud index $(1 - k_c)$ for this day is 0.92 during the 09 to 10 hour and 0.95 during the 13 to 14 hour which indicates a very cloudy day.

January 15, 2007

Hour	k_c and k_t
9:00 to 10:00am	k_t=0.04 k_c=0.08
1:00pm to 2:00pm	k_t=0.04 k_c=0.05

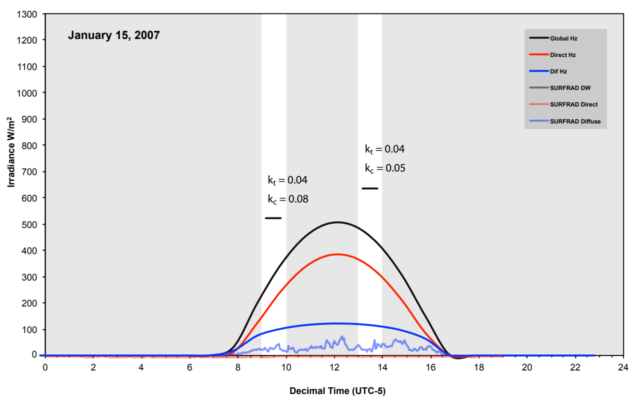

Fig. 4: BIRD Clear Sky Model compared against measured 3-minute average irradiance data from the Penn State SURFRAD data collection site.

3.4 <u>July 6, 2007</u>

Figure 5 shows July 6, 2007, with times of clear skies as well as other times of intermittent cloudiness. It is observed on this curve that the diffuse fraction increases when the beam fraction drops. Additionally, the beam SURFRAD data is lower than the beam Bird model curve. This presents an excellent opportunity to explore the meaning of each of the contributions, as well as an opportunity to identify the connection among the clear sky components and the deviations of those components by the measured data.

July 06, 2007

Hour	k_c and k_t
07 to 08	k_t=0.48 k_c=0.68
1:00pm to 2:00pm	k_t=0.81 k_c=0.96

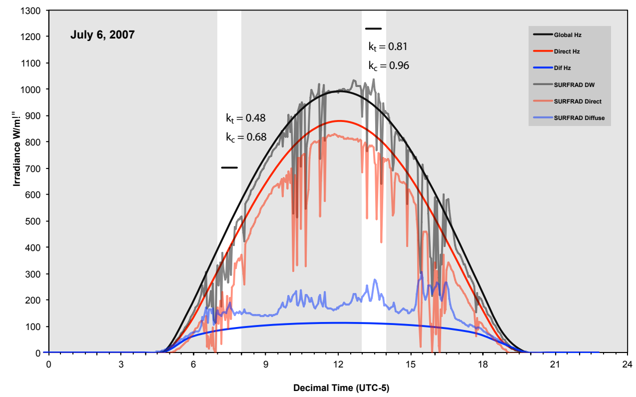

Fig. 5: BIRD Clear Sky Model compared against measured 3-minute irradiance data from the Penn State SURFRAD data collection site.

3.5 <u>July 15, 2007</u>

Figure 6 shows July 15, 2007, a day with intermittent clouds and a large thunderstorm. Yet, the hour from 7am to 8am in the morning shows a clearness index with relatively clear skies. One can observe a clear discrepancy between the measured data and the trend line for the initial beam and diffuse clear sky components, indicating a need to inquire into the parameters of the clear sky model. Again, an opportunity is identified to understand the meaning of the input parameters and their causal role in perturbing the components of shortwave irradiance.

July 06, 2007

Hour	k_c and k_t
7:00am to 8:00am	k_t=0.48 k_c=0.68
12:30pm to 1:30pm	k_t=0.19 k_c=0.22
1:30pm to 2:30pm	k_t=0.74 k_c=0.87
1:00pm to 2:00pm	k_t=0.48 k_c=0.57

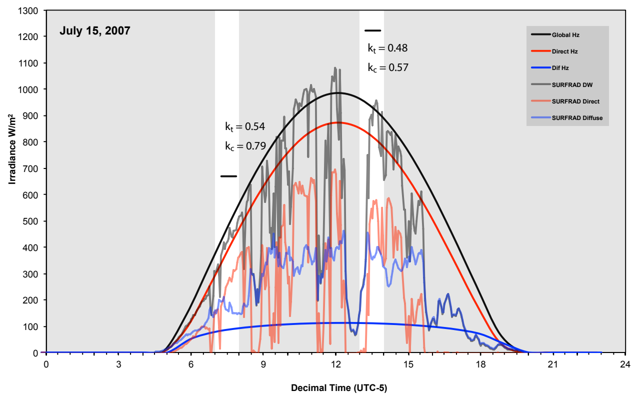

Fig. 6: BIRD Clear Sky Model compared against measured 3-minute irradiance data from the Penn State SURFRAD data collection site.

Figure 7 shows July 15, 2007 with a region of thunderstorm highlighted in red followed by a clearer period the following hour.

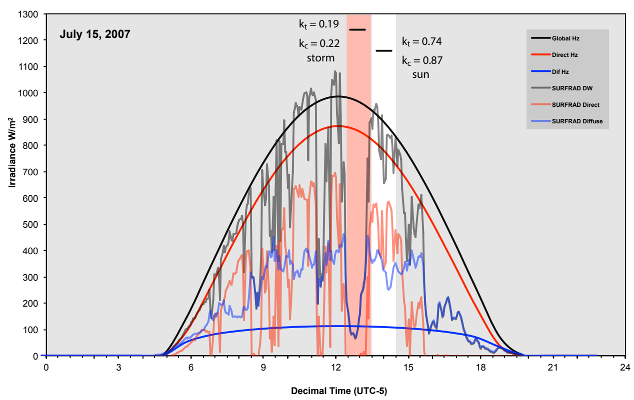

Fig. 7: BIRD Clear Sky Model compared against measured 3-minute irradiance data from the Penn State SURFRAD data collection site.

3.6 July 31, 2007

Figure 8 shows July 31, 2007 where the day is very clear and the SURFRAD data matches the Bird model closely.

July 06, 2007

Hour	k_c and k_t
7:00am to 8:00am	k_t=0.58 k_c=0.87
1:00pm to 2:00pm	k_t=0.80 k_c=0.95

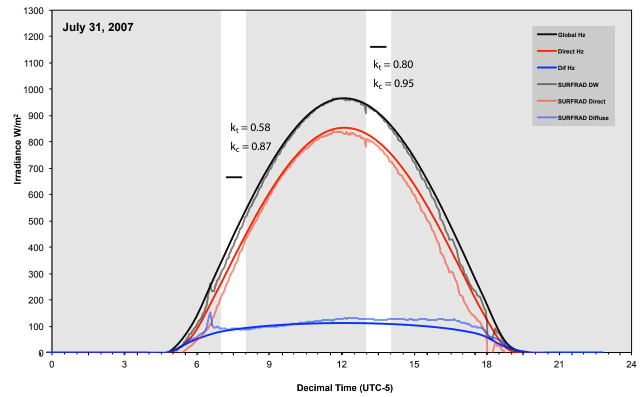

Fig. 8: BIRD Clear Sky Model compared against measured 3-minute irradiance data from the Penn State SURFRAD data collection site.

4. CONCLUSION

Inside the classroom for a solar design course, the raw solar data is not typically present. The use of hourly clearness indices is taught in classes to estimate the diffuse fractions of irradiation relative to GHI, and then the contribution horizontal irradiation (DHI). From these values we build many of our first models for irradiation incident upon a non-horizontal surface (isotropic model, HDKR model, Perez model). We observe that the k_T index, along with the hourly clear sky index are strongly correlated to the season of the geographic location where they are measured. There appears to be a significant educational value just from inspecting the raw data in comparison with first order estimates of clear sky conditions. New questions emerged in processing the data, including questions of data validation and quality flags, model validation against the data, and refinements of the clear sky data sets.

While these procedures may indeed be common or even overly simplistic to a working professional in the solar resource field, we find that an active learning approach working with the data and visualizing the results as a distribution of data has significant educational potential in contrast to the typical solar texts that tend to present only the summary statistics in dry form. For example, many of the parameters were not yet optimized to serve as a true clear sky estimation in this first evaluation. However, even the use of default settings permitted a line of inquiry into the correct use of a clear sky model relative to measured data based on recorded meteorological conditions. With data visualization and data exploration, students are encouraged to trouble shoot problems, and self-check their understanding of clear skies, AM0, components of light, as well as clearness and clear sky indices.

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6. REFERENCES

(1) SURFRAD, Accessed January 2013. Surface radiation network. FTP. ftp://ftp.srrb.noaa.gov/pub/data/surfrad/

(2) R. Perez, R. Aguiar, M. Collares-Pereira, D. Dumortier, V. Estrada-Cajigal, C. Gueymard, P. Ineichen, P. Littlefair, H. Lund, J. Michalsky, J. A. Olseth, D. Renné, A. Skartveit, F. Vignola, and A. Zelenka. "Solar resource assessment: A review". in *Solar Energy–The State of the Art: ISES Position Papers*, ed. Jeffrey M. Gordon. Earthscan, 2001. (3) T. Muneer *Solar Radiation and Daylight Models* Elsevier Butterworth-Heinemann, 2004. (4) Bird, Richard E., and Daryl R. Myers. Bird Clear Sky Model. NREL, 16 Aug. 2012.; Web. 24 Feb. 2013. URL http://rredc.nrel.gov/solar/models/clearsky (5) Duffie, J. A. and W. A. Beckman. *Solar Engineering of Thermal Processes*, 3rd ed., John Wiley and Sons, Inc., 2006.

(6) Amiran Ianetz and Avraham Kudish. *Modeling Solar Radiation at the Earth's Surface: Recent Advances*, chapter 4: A Method for Determining the Solar Global Irradiation on a Clear Day, pages 93-113. Springer, 2008.