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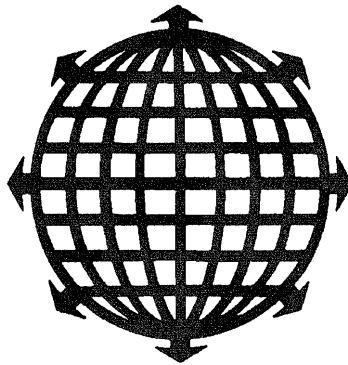
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HIGH-RESOLUTION MAPS OF SOLAR COLLECTOR PERFORMANCE USING A CLIMATOLOGICAL SOLAR RADIATION MODEL

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ABSTRACT

This paper will present a new methodology for producing estimates of the monthly and annual average performance of different types of flat-plate and concentrating solar collectors. The estimates are made on a uniform spatial grid with 40 km resolution. These estimates should be highly useful both to create maps to facilitate visualization of the solar resource, and as the basic data behind analytical studies of solar resources, deployment scenarios, CO2 mitigation strategies, and economic assessments. Our initial use of this methodology will be in the continental United States, where supporting data is available to evaluate the model outputs. In future years we hope to utilize this technique world-wide, especially in areas where the surface data are lacking.

The National Renewable Energy Laboratory (NREL, Golden, CO) has developed the Climatological Solar Radiation (CSR) model to estimate climatological averages of daily-total solar radiation at a 40 km spatial resolution (1). The CSR model is operational and has been usefully applied to the United States as well as several international areas. The model uses, as input, monthly climatological mean values of cloud cover, precipitable water vapor, aerosol optical depth, surface albedo, and total column ozone. These input parameters are available from various sources such as NASA and NCDC (National Climatic Data Center).

The outputs from the original version of CSR are monthly mean daily total values of Global Horizontal, Direct Normal, and Diffuse radiation. Our latest revision to the model allows us to calculate the monthly mean output for the various collector types such as tilted flat-plate surfaces, one- and two- axis flat-plate collectors, and concentrating collectors.

Summarized hourly data for these orientations are available in the "Solar Radiation Data Manual for Flat-plate and Concentrating Collectors". These were produced for the 239 individual sites in the United States National Solar Radiation Data Base (NSRDB). Maps of the output from the various collectors are available on the NREL Renewable Resource Data Center web site (rredc.nrel.gov). Our new CSR model output maps will look similar to these, but with 40 km resolution, using over 10,000 grid points for the USA alone. At this writing, we have modeled and made evaluations of two types of solar collectors, a flat-plate (PV) system facing south with tilt=latitude, and a one-axis tracking concentrator (solar thermal parabolic trough) oriented in a North-South direction. We present here an evaluation of these two types of collectors, as well as for Global Horizontal (PV system with tilt = 0 degrees) and Direct Normal (2-axis tracking concentrator). We also present preliminary sample maps of the United States for these collector types.

1. BACKGROUND

A key mission of the NREL Resource Assessment function is to create new techniques for estimating solar resources at any location. The principal product of this effort has been the U.S. National Solar Radiation Data Base (NSRDB) (2), which contains hourly modeled and measured radiation data, as well as useful meteorological parameters, for 1961-1990. These time series data were created for 239 stations in the United States, Puerto Rico and Guam. This includes 213 stations in the contiguous United States. An important practical application of the NSRDB is the "Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors" (3).

In the last 3 years, NREL has also been producing maps of Global Horizontal, Direct Normal, and Diffuse solar radiation using a different technique called the "Solar Radiation Data Grid" (1). This procedure uses the NREL Climatological Solar Radiation (CSR) model, with input data derived from the best available climatological data, for all locations.

For this study, we were able to use the NSRDB and the Solar Radiation Data Manual to provide crucial verification data sets, as well as test input data for the CSR model.

Cloud cover data for the Solar Data Grid come from the Real-Time Nephanalysis (RTNEPH) database. The RTNEPH database originates at the Air Force Global Weather Center (AFGWC) at Offutt Air Force Base, Nebraska. RTNEPH consists of global cloud analyses that produce cloud information every three hours at a nominal 40-km resolution. The AFGWC cloud analyses use all available data including surface observations, polar orbiting satellite data, and upper air data to produce cloud cover estimates for Total clouds as well as Low, Middle, and High clouds.

We use a histogram database formed from RTNEPH data for the period from 1985 to 1991. The RTNEPH histogram database gives the number of occurrences of low, middle, high, and total cloud amounts in increments of 5% from 0% to 100% for each month and each 3-hour observation time. Each histogram combines all cloud observations, for that month and time, in the entire seven year period. The histograms of total cloud cover for hours between sunrise and sunset were used to determine monthly average total cloud cover during daytime hours. The histograms for low, middle, and high cloud layers were used to estimate monthly average opaque cloud cover.

Atmospheric pressure is estimated from elevation data, which are available worldwide at 5-minute (9- km) resolution (4). Worldwide *surface albedo* data are available from several sources, including the Canadian Center for Remote Sensing (CCRS), which was used here (5). The CCRS data have a resolution of 280 km. *Ozone* data are available on a CD-ROM produced by the National Oceanic and Atmospheric Administration (NOAA) (6). These data are from the Total Ozone Mapping Spectrometer (TOMS) and cover the period from 1979 to 1988 for a 1° latitude by 1.25° longitude grid.

Precipitable water vapor data are available from several sources including radiosonde data from individual weather stations. For the contiguous U. S., 30 year datasets from radiosonde stations, used in the NSRDB project, were summarized and used as inputs.

Aerosol optical depth data are estimated from direct normal solar radiation data and other sources. For the results presented here, aerosol optical depth was also taken from the NSRDB estimates, based on the available record of direct normal radiation for 30 stations in the U. S. (7).

2. THE CSR MODEL

The CSR model is a simplified version of the METSTAT model that was used to produce the NSRDB for the United States (8). Using the METSTAT algorithms, the CSR model calculates solar radiation energy for each 5-minute period from sunrise to sunset and then summarizes the 5-minute values to obtain a daily-total value. The 5-minute calculations are performed only for one day of each month, the day for which the daily-total extraterrestrial radiation (ETR) equals the monthly average daily-total ETR.

The current version of the CSR model uses only mean values for all daylight hours as inputs to the model. There are two major assumptions inherent in the use of this technique for estimating climatological averages.

The first assumption is that the CSR model, using only mean values as inputs and using only one day to represent 30 years, can produce averages representative of the 30 year means of the output parameters. This implies that there are not serious non-linearities in the model. For example, for all locations and all months, the model will be run on partly cloudy conditions, since the input is the average of all days. An average cloudiness of (e.g) 40% is actually the result of a distribution of some totally clear days, some overcast days, and a few partly cloudy days. The CSR model will be effective only if the predicted radiation with 40% cloud cover is close to the average radiation with all cloud covers.

To assess the validity of this "Climatological Model Assumption", we have prepared a dataset with input values based on the 30 year mean of the NSRDB stations, for each of the 213 verification stations in the contiguous United States. This dataset does not use RTNEPH or any spatially derived input data, other than the data used in the NSRDB. We will refer to this test input data set as "NSRDB Inputs".

As we introduce each new solar collector type from the Solar Radiation Data Manual, we will first evaluate CSR model results using NSRDB inputs against the 30 year average tilted surface calculations in the Solar Radiation Data Manual. The residual differences should be due mostly to the Climatological Model Assumption.

The accuracy of the output maps from the Solar Data Grid

project is subject to a further assumption, which we will call the "Data Grid Assumption". This measures whether or not we can create input data on a 40 km grid that represents the actual climate statistics for the location in question. Verification of the maps is more difficult than verification of the model, since no surface location can truly represent any one 40 km grid cell. We will present verification statistics using the Data Grid (RTNEPH) inputs, for the Data Grid 40 km cell nearest to each NSRDB surface station. We would expect larger errors for the Data Grid statistics than for the NSRDB statistics.

2.1 Preparation of Input Data

As noted earlier, the various model input data come with resolutions varying from 9 km (elevation-pressure) to 280 km (albedo). Because cloud cover plays a dominant role in determining solar radiation at the Earth's surface, the 40-km polar projection grid of the RTNEPH database was selected for both the input and output grids of the CSR model. All of the non-cloud cover data inputs are resampled such that input values for all variables are available for each RTNEPH 40-km cell.

2.2 CSR Model Algorithms

The following is a condensed version of the model description given at the 1998 ASES conference (1). We have added one step to the model, the calculation of tilted surfaces. For each month, CSR calculations proceed through the following steps:

Step 1 - Solar Geometry -The date and the latitude and longitude of a cell are used to calculate the solar elevation and azimuth for each 5-minute time step throughout the day.

Step 2 - Direct-Beam and Diffuse Transmittances -Direct-beam transmittance algorithms include the effects of Rayleigh scattering (T_R), ozone absorption (T_O), uniformly mixed gas absorption (T_{UM}), water vapor absorption (T_W), aerosol absorption and scattering (T_A), opaque cloud absorption (T_{OPQ}), and translucent cloud absorption (T_{TRN}). Diffuse sky transmittance algorithms include contributions from Rayleigh scattering (Ks_R), aerosol scattering (Ks_A), opaque cloud scattering (Ks_{OPQ}), translucent cloud scattering (Ks_{TRN}), and multiple ground-to- atmosphere/cloud reflectances (Ks_{GRFL}).

Step 3 - Combining Transmittances - The algorithms to combine direct-beam and diffuse transmittances are:

$$Kn = T_R \, T_O \, T_{UM} \, T_W \, T_A \, T_{OPQ} \, T_{TRN}$$

$$Ks = (Ks_R + Ks_A) \, f_m$$

$$Kd = (Ks + Ks_{OPQ} + Ks_{TRN}) + Ks_{GRFL}$$

$$Kt = Kn + Kd$$

where Kt, Kn, and Kd are transmittances for global horizontal, direct normal, and diffuse horizontal solar radiation, respectively, and f_m is an empirical air mass function.

Step 4 - Calculating Solar Radiation Intensity - Solar radiation intensity for each 5-minute period is calculated by multiplying transmittances by ETR and ETRN (extraterrestrial solar radiation on a surface normal to the sun),

$$In = ETRN \; Kn$$

$$Id = ETR \; Kd$$

$$It = ETR \; Kt$$

where ETRN, ETR, In, Id, and It are in Watts/m^2.

Step 5 – Calculating tilted surface radiation intensity – These calculations are done using the same equations and software as in the "Solar Radiation Data Manual..." (3). Flat-Plate radiation is a combination of Direct, Diffuse, and radiation reflected from the surface in front of the collector. Diffuse sky radiation on a tilted surface is modeled using the method of Perez (9). Radiation for concentrating collectors is a simpler matter of computing the incidence angle and multiplying its cosine by the direct normal component. These computations are also carried out for each 5-minute period.

Step 6 - Calculating Daily-Total Energy
For the final step, the daily-total solar radiation energy in Watt-hours/m^2 is calculated by integrating the 5-minute radiance values through all daylight hours.

3. EVALUATION OF RESULTS

The first set of model runs used NSRDB inputs, with monthly average cloud cover values **and** opaque cloud amounts from directly observed hourly cloud observations. These results represent a test of the Climatological Model Assumption.

The second or "Data Grid" model runs used monthly average cloud cover values derived from the RTNEPH histogram database. The opaque cloud amounts used in these model runs were parameterized from layered cloud amounts in the RTNEPH database.

For each input data set, we performed two sets of model runs, one for the flat-plate with tilt=latitude, which we refer to as "Tilt", and one for the 1-Axis trough collector oriented N-S, which we call "C1NS". In Table 1, we summarize the results for all months, for each of the 4 runs. For comparison, we also include the results for Global Horizontal (GLO) and Direct Normal (DIR) radiation. Note that these results represent the mean of 12 monthly residuals, not the residuals of the annual means.

The results show that the Tilt calculations have an increased bias of 2.4% over Global Horizontal. The tilted surface calculation using the CSR model with NSRDB inputs averages 3.5% greater than the Data Manual results based on hourly calculations. This possibly indicates a non-linearity in the model (including the Perez tilted surface algorithms) which makes the "Climatological Assumption" questionable for this collector orientation. The standard deviations for Tilt are also slightly greater than for Global Horizontal. We suspect the differences are related to the sensitivity of the Perez diffuse algorithms and the ground reflected component to surface albedo. Further analysis will be necessary.

The results for the 1-axis tracking concentrator with a North-South axis (C1NS) do not show similar problems. The mean bias is very low for the NSRDB inputs, indicating that the Climatological Assumption holds for this collector. The results are very close to those for Direct Normal.

Table 2 shows the underlying monthly data for Table 1, for those interested in seasonal differences. For almost all cases, the percent residual errors are greatest in the winter

TABLE 1 – MEAN BIAS ERROR AND STANDARD DEVIATION FOR ALL MONTHS.

Model Run	Mean Bias Error	Std Deviation
Tilt – NSRDB	+3.5%	2.7%
Tilt – Data Grid	+2.6%	4.5%
GLO – NSRDB	+1.1%	2.6%
GLO – Data Grid	+0.6%	3.7%
C1NS – NSRDB	+0.1%	1.9%
C1NS – Data Grid	-2.0%	7.3%
DIR – NSRDB	+0.5%	1.8%
DIR – Data Grid	-1.7%	7.2%

and lowest in the summer. For Tilt, the bias error is low in the summer, and between 4% and 5% the rest of the year. Since the underlying uncertainty of results from the NSRDB and Solar Radiation Data Manual are + or - 9%, the new results may be considered statistically equivalent to the Solar Radiation Data Manual results. However, we will still be concerned with reducing the errors in the new data before using them extensively.

The 1-Axis Concentrator results, however, have about the same quality as our Direct Normal outputs, and can be used in the same way.

TABLE 2 -PERCENTAGE ERRORS FOR EACH MONTH, MEAN BIAS AND STANDARD DEVIATION. ALL VALUES ARE CSR MODEL MINUS NSRDB.

	Tilt – DataGrid - Bias	Tilt – Data Grid - StDev	Tilt - NSRDB - Bias	Tilt - NSRDB - StDev	C1NS - Data Grid - Bias	C1NS - Data Grid - StDev	C1NS – NSRDB - Bias	C1NS - NSRDB - StDev
jan	3.3%	8.3%	4.1%	4.4%	-3.6%	13.2%	-1.7%	2.6%
feb	2.0%	6.3%	4.6%	4.0%	-6.2%	8.1%	-0.6%	2.0%
mar	4.5%	5.0%	3.8%	3.0%	3.3%	7.2%	1.7%	1.5%
apr	4.5%	4.2%	4.1%	2.6%	2.3%	7.5%	1.7%	1.5%
may	1.8%	3.3%	3.1%	2.6%	-3.0%	5.7%	0.9%	1.5%
jun	1.5%	3.0%	1.4%	2.3%	-0.2%	5.2%	-0.1%	1.8%
jul	-0.1%	3.2%	0.6%	2.4%	-2.8%	5.3%	-0.7%	2.0%
aug	0.2%	3.2%	1.5%	2.3%	-2.7%	5.8%	0.3%	2.0%
sep	3.4%	2.9%	4.8%	2.4%	-1.4%	5.2%	1.9%	1.6%
oct	3.6%	2.8%	4.7%	1.7%	-1.7%	5.7%	0.5%	1.8%
nov	1.2%	4.9%	4.8%	2.1%	-7.6%	10.0%	-0.1%	2.1%
dec	5.5%	6.4%	4.2%	3.2%	-0.2%	9.1%	-2.2%	2.5%
Ann	2.6%	4.5%	3.5%	2.7%	-2.0%	7.3%	0.1%	1.9%

CSR Annual Global, Tilt = Latitude

Watt Hours per Sq Meter per Day
- 2000 - 3000
- 3000 - 4000
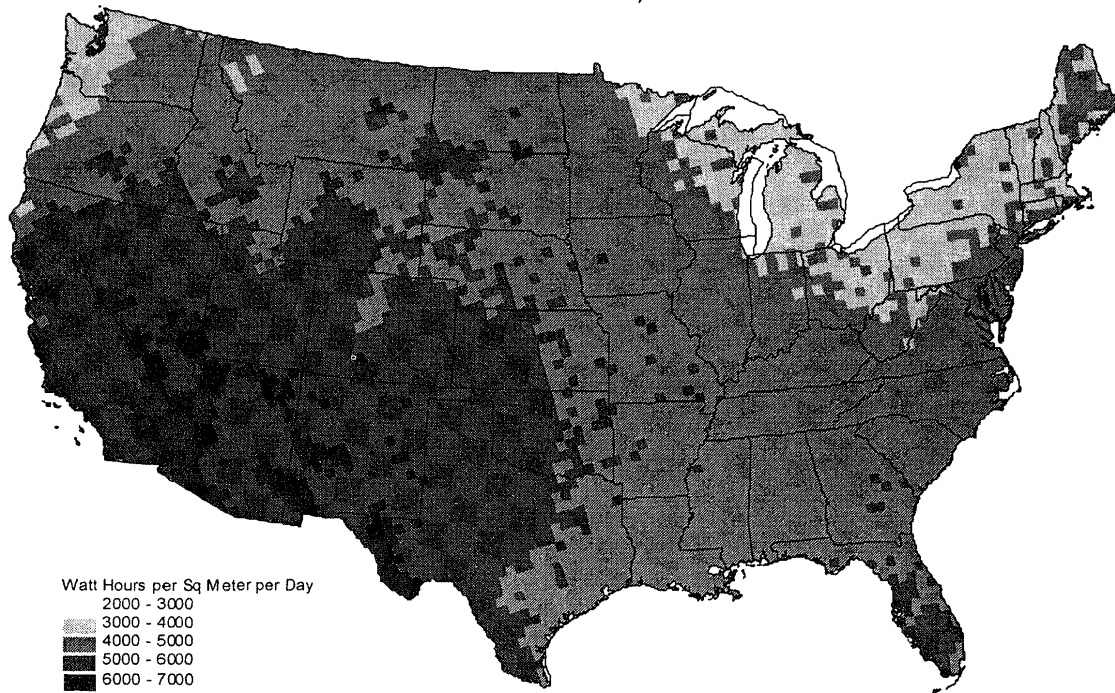- 4000 - 5000
- 5000 - 6000
- 6000 - 7000

Fig. 1 – PRELIMINARY example U.S. map showing average annual radiation for a flat plate collector, facing south, with tilt=latitude. Data from NREL Data Grid using CSR model..

4. OUTPUT MAPS

The maps in figures 1 and 2 are preliminary example maps based on the current state of the CSR model and input datasets. They are qualitatively similar to the maps available from the NREL web site (rredc.nrel.gov), but of course show much more detail due to the 40 km resolution.

The map for a flat-plate collector with tilt=latitude (Figure 1) shows some degree of bias , with slightly higher values almost everywhere, compared to the Data Manual maps available on the web.

The map for a 1-axis tracking concentrator does not show a bias, and exhibits considerable detail in the Southwestern U. S., the primary candidate region for deployment of this type of solar technology.

While the example U. S. maps shown will be useful, the real value of the collector data grids will be in regional studies, spatial analysis of deployment opportunities and niche markets, CO_2 mitigation calculations, etc., using the digital data sets.

Our short-term plans for this technology include implementing and testing more of the collector types in the data manual, and possibly installing a PV performance module into the CSR model. This would allow us to create data grids directly usable for economic and deployment studies.

5. ACKNOWLEDGEMENTS

CSR Annual 1-Axis Concentrator, Oriented N-S

Watt Hours per Sq Meter per Day
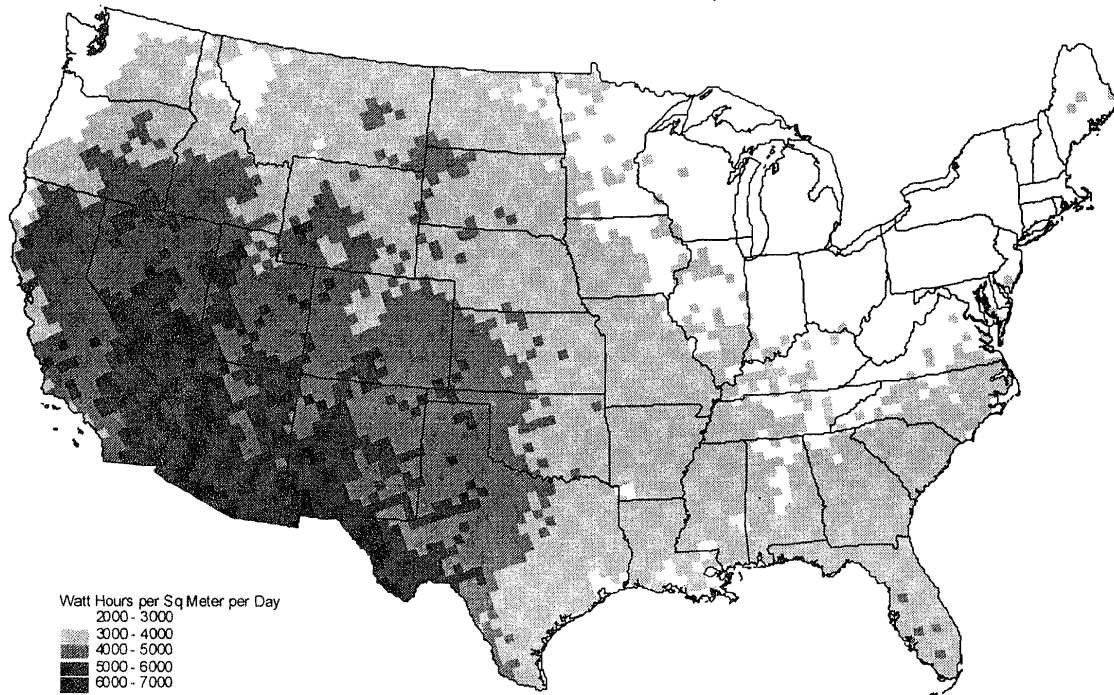2000 - 3000
3000 - 4000
4000 - 5000
5000 - 6000
6000 - 7000

Fig. 3 – PRELIMINARY example U. S. map showing annual average radiation for a 1-Axis Concentrator, Oriented N-S. Data from the NREL Data Grid using the CSR model

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