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A NEW METHOD FOR DETERMINING SUB-HOURLY SOLAR RADIATION FROM HOURLY DATA

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ABSTRACT

Accurately computing the solar irradiance in building performance software (BSP) is necessary to reliably predict the thermal behavior of many building related processes as well as the performance of renewable energy generators. While most of the simulations are performed at higher resolutions, up to 1-minute, the solar radiation data is often provided with weather data files at an hourly time scale. This work investigates the way popular building simulation programs interpolate the hourly solar radiation data and proposes a new algorithm that fixes deficiencies of other common methods. Program algorithms are identified and described and compared against high resolution measured irradiation data for three stations in the United States.

INTRODUCTION

While solar radiation data included in standard weather files is in hourly increments, a variety of energy analysis require sub-hourly timesteps. This is the case of solar farms where high temporal resolution is instrumental to the planning and operational phases of utilities. This has been addressed by generating synthetic high temporal datasets from hourly data (Bright et al. 2015; Fernández-Peruchena & Gastón 2016; Grantham et al. 2017).

While Building Performance Simulation (BPS) tools originally used hourly timesteps in line with the most common weather data timesteps, they have now evolved and often rely on subhourly time steps to model physical processes such as daylighting and Heating, Ventilation and Air-Conditioning (HVAC) systems and controls. Algorithms currently used in BPS programs to determine the sub-hourly radiation data produce an unrealistic shape for the radiation with discontinuities or fail to repeat the data from the weather file (McDowell & Kummert 2016).

Problem

For most weather file formats, the solar radiation data is provided as the integrated radiation over the previous data interval. If a BPS tool is performing a heat balance analysis over an hourly timestep, the heat flux at a surface received during the timestep will be the average over the timestep, which is exactly what is provided in the data file. Things get trickier when the timestep of the BPS is less than an hour. There are two potential issues in determining the solar radiation in sub-hourly timesteps: ensuring that the total solar radiation over the hour matches the information in the data file (i.e. keeping the total energy received consistent) including during the sunup and sundown periods and providing a “realistic” shape to the radiation data without discontinuities. The first is easy to check by integrating the calculated horizontal sub-hourly solar radiation and comparing this to the values in the data file. The second is more difficult as “realistic” is a subjective term and without sub-hourly measurements, the exact shape of the radiation over the hour is not known. So any shape of the sub-hourly radiation could be “realistic” as long as it avoids discontinuities.

Common weather file formats include the total radiation on a horizontal surface, diffuse radiation on a horizontal surface and direct normal radiation. This data is redundant, as only two of these three values are needed to calculate solar incident radiation on tilted surfaces, since the position of the sun can be calculated accurately from time and location. Typically, programs use the diffuse on the horizontal and the direct normal to determine the horizontal solar radiation values, because traditionally the measured values for these two parameters are the most accurate. However, since the solar radiation data in most weather files is now modeled and not measured, the values should be consistent.

Existing Methods

Since the data from the weather file is the total over an hour, it can be represented as constant over the hour at the value from the file. This appears as a stair-step pattern as shown in Figure 1.

Two methods currently used in BPS programs are (i) linear interpolation through the midpoint and (ii) shaping based on the extraterrestrial radiation profile. Linear interpolation using the hourly total as the midpoint during the hour results in a piecewise linear shape as shown in Figure 2 (the three vertical lines in the Figure represent sunrise, solar noon, and sunset, from left to right). This method produces a nice smooth shape for the radiation but does not result in the same hourly total as from the data file at all times. EnergyPlus follows this particular method.

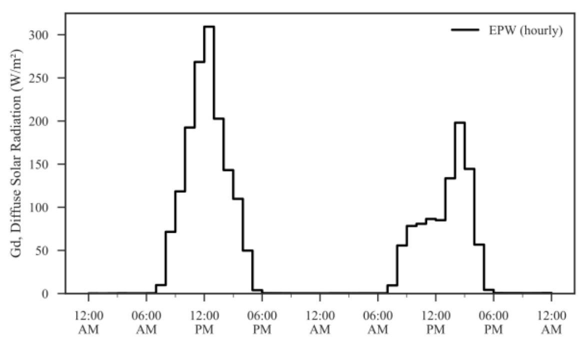

Figure 1 Stair-step pattern

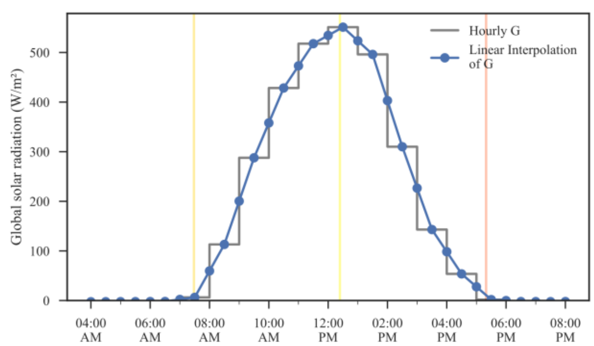

Figure 2 Piece-wise linear interpolation through the midpoint; This method is used by EnergyPlus

The extraterrestrial solar radiation has a definitive shape based on the time of the year and the time of the day. The method used by TRNSYS 17's solar calculation engine is to use that profile to shape the interpolated diffuse horizontal while preserving the average value over the time step. This conserves the hourly integrated value and results in a smooth and realistic profile for uniformly clear or covered days, but it creates a shaped profile with a saw-tooth pattern as shown in Figure 3 for days with variable cloud cover. This method does result in the same hourly radiation totals as the data file but creates an unrealistic shape with possible discontinuities at some hours.

There has been some work on this issue for specific regions or applications, but they have either made use of additional measurements or climate region information that is not available in the standard weather data files (Grantham et al. 2017, Bright et al. 2015, Fernandez-Perchena et al. 2016) or are focused on the generation of solar data from other measurements (Larraneta et al. 2018, Ngoko et al. 2014, Hofmann et al. 2014, Polo et al. 2011, Larraneta et al. 2015). Because of the additional data required in these techniques, they do not lend themselves to generalized application in Building Energy Modeling (BEM) software for standard weather files.

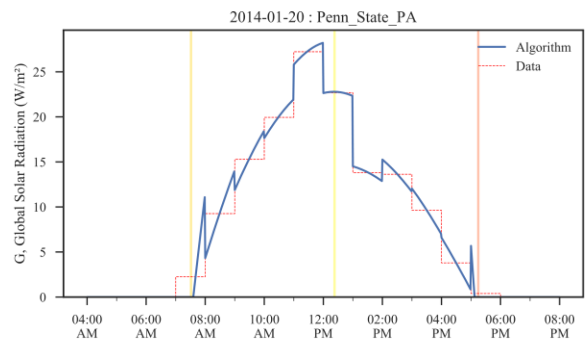

Figure 3 Saw-tooth Pattern produced by TRNSYS 17's algorithm

POSSIBLE METHODS

The problem posed is one where the data is an hourly total and we know that the radiation is 0 at sunup and sundown times (which are simply a function of location and time of year), but there are no other points known between the sunup and sundown times. This means there is an infinite number of hourly endpoints and shapes that return the hourly total. However, when further restrained to never having a negative value and producing a "realistic" shape to the radiation, the solution gets much more difficult.

As with the existing method using the shape of the extraterrestrial radiation, the sub-hourly shape can be based on some other physical measurement and forced to match the hourly total. However, since these algorithms are based on hourly calculations, they do not produce a "realistic" shape when applied sub-hourly, typically including discontinuities at the hourly intervals. Without more detailed information on the physical shape of the radiation, these physical-based techniques will not return something that would be considered a "realistic" shape.

Once we have discarded physical-based shaping algorithms, we are left with mathematical-based algorithms. The difficulty with the mathematical-based methods is that they don't have the limits of the physical-based methods. So these limits must be included in any algorithm that is developed, primarily matching the hourly totals, being zero at sunup and sundown, and not being negative.

An initial technique is knowing that the radiation is zero at sunup and the total over that hour, the endpoint for that hour can be determined assuming a linear profile. This gives the startpoint for the next hour and knowing the total for that hour we can calculate the endpoint assuming a linear profile and continue for the rest of the day ending with 0 solar radiation at the sundown time. However, this method produces negative radiation values and produces a jagged shape to the radiation profile in the afternoon (see Figure 4). This is true because by only looking at the current value it is not clear when you have passed the peak during the day and should start having a lower endpoint for the hour.

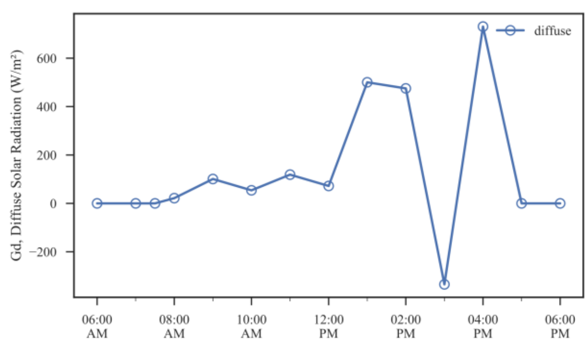

Figure 4 Linear interpolation can produce negative values and a jagged profile in the afternoon

An extension of this algorithm is to use the totals for both the current hour and the next hour to find an endpoint. Then the midpoint radiation value during the hour is the point required to produce the correct hourly total. This algorithm greatly improves the shape of the radiation and avoids most of the negative radiation values. Details of this algorithm will be given in the next section.

PROPOSED ALGORITHM

We assume that the data file contains hourly irradiation values (integral of the incident radiation), denoted by H (in Wh/m² over one hour). The proposed algorithm will calculate the irradiation over each sub-hourly time step from a reconstructed profile of the instantaneous solar radiation G (in W/m²).

The most straightforward part of the algorithm is to set the solar radiation to 0 for any timesteps that occur completely prior to sunup or after sundown. For all other timesteps it is necessary to determine the startpoint and endpoint for the data period. The startpoint is also straightforward as it is 0 at sunup and for other data periods it is the endpoint of the previous data period.

For the data period that includes sunup, if the solar radiation in the next data interval is higher than the amount in the current data interval, the endpoint is calculated as:

$$G_{end} = \frac{2*H_n}{t_{end}-t_{start}} \tag{1}$$

If the radiation in the next hour is less than the current hour, the endpoint is calculated as:

$$G_{end} = \frac{0.25*H_n+0.75*H_{n+1}}{t_{end}-t_{start}} \tag{2}$$

For the normal data periods where there is solar radiation and it is between sunup and sundown the endpoint is calculated as:

$$G_{end} = \frac{0.5*H_n+ 0.5*H_{n+1}}{t_{end}-t_{start}} \tag{3}$$

For the data periods including the sundown time, first the endtime is adjusted to be the end of the timestep which contains the sundown time. Then the endpoint is simply set to 0.

Determining the Data Period Midpoint

The midpoint for the data period depends on the number of timesteps in the data period. The number of timesteps is determined by subtracting the starttime from the endtime (after adjusting for sunup and sundown, if necessary) and then dividing by the length of the timestep.

If there is only one timestep in the data time period then the instantaneous radiation at the midpoint has to be the total irradiation divided by the length of the timestep :

$$G_{mid} = \frac{H_n}{\delta t} \tag{4}$$

If there are at least 2 timesteps in the data time period, then we need to determine when the midpoint occurs. We need the midpoint to fall at the end of a timestep to ensure that we maintain the correct total irradiation during the data period. To do this, we can simply integer divide the number of timesteps in the data period by 2. So if there are 4 timesteps in the data period then the midpoint will fall at the end of the second timestep and if there are 5 timesteps the midpoint will also fall at the end of the second timestep. With the time of the midpoint calculated the midpoint value is calculated using :

$$G_{mid} = \frac{2*H_n}{N*\delta t} - \frac{N_{mid}*G_{start}}{N} - \frac{(N-N_{mid})*G_{end}}{N} \tag{5}$$

At this point, it is important to check if the calculation has resulted in a negative midpoint. If so, then the midpoint is adjusted to a value that is constant during the time period between the end of the first timestep of the data period to the end of the second-to-last timestep of the data period. This constant value is calculated to maintain the correct total radiation over the entire data period using:

$$G_{mid} = \frac{2.0 * \frac{H_n}{\delta t} - (G_{start} + G_{end})}{2.0 * (N-1)} \quad (6)$$

If the midpoint is still negative, it is assumed that the radiation will drop to 0 at the end of the second timestep.

During the simulation, the instantaneous radiation values are determined by linearly interpolating between the startpoint and the midpoint - if before the midtime - and between the midpoint and the endpoint - if after the midtime. Since BPS tools require the average radiation value over the timestep (or the total irradiation over the timestep), the reconstructed piecewise linear instantaneous profile is averaged over each timestep by using the mean value between the beginning and the end of each timestep.

Example

To show the algorithm in action we will work through a small example. Take the horizontal diffuse irradiation data shown in Table 1. On this day in this location sunrise is at 7:30 and sunset is at 16:30 and we will assume 5 timesteps per hour (i.e. 12-min timesteps). Remember that the data is given as the total irradiation over the previous period (so the value of 10.8 at 8:00 means that 10.8 Wh/m^2 of irradiation was incident during the hour from 7:00 to 8:00).

Table 2 shows how the algorithm would set the starttime, endtime, startpoint, endpoint and midpoint based on the data. Note that for the hour from 14:00 to 15:00, the calculated midpoint is negative and would be adjusted to be a constant 72.225 W/m² from the 2nd timestep to the 4th timestep. Figure 5 shows the plot of the reconstructed instantaneous radiation profile versus the algorithm output. We observe that the algorithm yields a natural shape for the solar component and eliminates any discontinuities.

Table 1 Solar Radiation Data

Hour	Horizontal Diffuse (Wh/m^2)
7.00	-
8.00	10.80
9.00	122.40
10.00	154.80
11.00	172.80
12.00	190.80
13.00	572.40
14.00	975.60
15.00	140.40
16.00	396.00
17.00	39.60
18.00	-

Table 2 Algorithm calculations

Time		H (Wh/m^2)		G (W/m^2)		
Start (t_{start})	End (t_{end})	Now (H_n)	Next (H_{n+1})	Start (G_{start})	End (G_{end})	Mid (G_{mid})
7:24	8:00	10.8	122.4	0	36.0	12.0
8:00	9:00	122.4	154.8	36.0	138.6	147.2
9:00	10:00	154.8	172.8	138.6	163.8	155.9
10:00	11:00	172.8	190.8	163.8	181.8	171.0
11:00	12:00	190.8	572.4	181.8	381.6	79.9
12:00	13:00	572.4	975.6	381.6	774.0	527.8
13:00	14:00	975.6	140.4	774.0	558.0	1306.8
14:00	15:00	140.4	396.0	558.0	268.2	-103.3
15:00	16:00	396.0	39.6	268.2	217.8	554.0
16:00	16:36	39.6	-	217.8	0	59.4

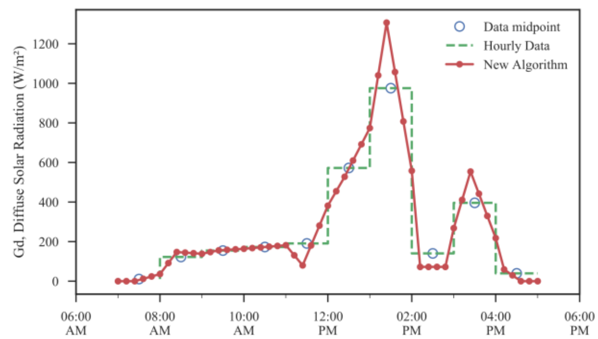

Figure 5 Proposed algorithm versus hourly mean of measured data for the diffuse component (G_d)

Figure 6 shows the reconstructed instantaneous profile with the average values over each time step, in addition to the original hourly integrals.

The performance of this algorithm is assessed in the next section by evaluating the method against measured 1-minute solar radiation data.

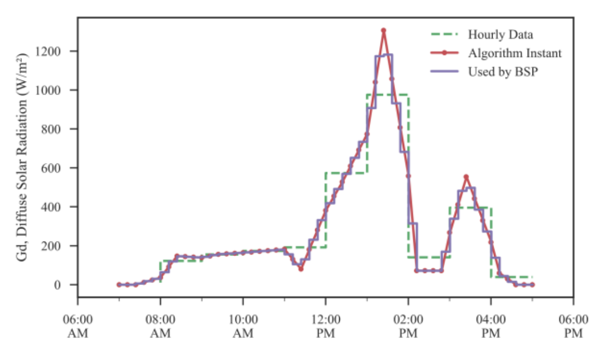

Figure 6 Average value over each timestep and instantaneous values

EXPERIMENTAL DATA

Surface radiation measured data (minute timestep) is taken from the National Oceanic and Atmospheric

Administration (NOAA). Datasets are maintained for 11 weather stations scattered across the United States since 1998. For this study, Penn State, PA, Fort Peck, MT and Goodwin Creek, MA were chosen.

Although the SURFRAD datasets have their own methodology to process and validate the data, a second pre-processing was performed to prepare the data for BPS programs. As a first step, negative solar radiation data points for the global horizontal, direct normal and total horizontal diffuse radiation components (G, G_{bn} and G_d) were forced to zero. These negative values are a result of the instruments used to measure solar radiation: during the night, pyrometers and pyrheliometers tend to exchange with the night sky which results in a negative measurement that can go as high as -30 W/m^2 (National Oceanic and Atmospheric Administration, n.d.). Furthermore, values flagged as missing or erroneous by NOAA were replaced with physically possible values to allow for a smooth operation of each software, but flagged as to be removed in the statistical analysis of the datasets. Large gaps due to missing or incomplete data were systematically replaced with the data from the next day, making sure subsequent days were not repeated.

Minute-to-minute timesteps were then averaged over an hour for all solar radiation data points as well as important weather-related components given with the SURFRAD data. Such components include the dry bulb temperature, relative humidity, atmospheric pressure, wind direction and wind speed. After processing and cleaning the data, custom EPW files were created by using existing TMY3 locations as a canvas. Data points were then replaced in the file. Latitude, longitude and timezone information were also adjusted when necessary. A total of 207775, 253657 and 256178 datapoints for Goodwin Creek, Fort Peck and Penn State respectively met all criteria, and served as the main database for the statistical analysis.

RESULTS

The three methods (EnergyPlus, TRNSYS 17 and TRNSYS 18) were run with the three cities with the custom weather files. Figure 7, Figure , and Figure 8 show the daily results for the three programs along with the measured data for horizontal diffuse, beam and total solar radiation for three different days (January 4th, July 16th, and September 27th). The graphs show that the EnergyPlus and TRNSYS 18 methods produce profiles which are smoother and without discontinuities. The TRNSYS 17 method demonstrates the characteristic saw-tooth pattern from using the extraterrestrial profile to shape the radiation. It is interesting to look at the measured solar radiation and observe that in the presence of clouds the actual solar radiation is definitely not smooth and a more "realistic" solar profile may include much more variation.

A comparison of the hourly integrated radiation values from the three programs versus the measured data for July 16th at Fort Peck is shown in Table 3. The values in the table are normalized versus the measured data so that a value of 1.00 indicates agreement between the BPS hourly integrated values and the hourly integrated measured data. Anything other than 1.00 indicates that the BPS output differed from the data in the weather file. The results show that the new TRNSYS 18 algorithm provides the best agreement with the data in the weather file and EnergyPlus shows the largest disagreement.

A statistical analysis of the algorithm results versus the measured data was also performed. Results from the statistical analysis (

Table 4) reveal that EnergyPlus shows the highest deviation from the measurements when using a linear interpolation method (as high as 5.15%). On the other hand, TRNSYS 17 and TRNSYS 18 manage to keep a good annual representation with their respective methods that try to respect the hourly mean given by the weather file.

CONCLUSION

Current BPS programs do not calculate the sub-hourly solar radiation in ways that preserve the hourly sums in the weather file nor have "realistic" shapes. This paper presented a new algorithm that preserves the hourly sums from the weather data files and produces a smoother shape with no discontinuities. This new method has been incorporated in version 18 of the TRNSYS software package.

NOMENCLATURE

G_o – Extraterrestrial horizontal radiation [W/m²]
G_{bn} – Beam normal solar radiation [W/m²]
G_d – Diffuse horizontal solar radiation [W/m²]
G – Global (total) horizontal solar radiation [W/m²]

Hourly integrated solar irradiation

H_n – Solar irradiation at current data interval [Wh/m²]

H_{n+1} – Solar irradiation at next data interval [Wh/m²]

G_{start} – Solar radiation at the start of current data interval [W/m²]

G_{mid} – Solar radiation at the midpoint of the current data interval [W/m²]

G_{end} – Solar radiation at the end of the current data interval [W/m²]

Other variables

δt – the timestep of the BPS simulation [h]

N – the number of timesteps in the data interval adjusted for sunup and sundown times if necessary [-]

N_{mid} – the number of the timestep at the end of which is the midpoint interpolation value of the data interval (found by integer dividing the number of timesteps in the data interval by 2) [-]

t_{end} – the time at the end of the current data interval adjusted for sundown if necessary [h]

t_{start} – the time at the start of the current data interval adjust for sunup if necessary [h]

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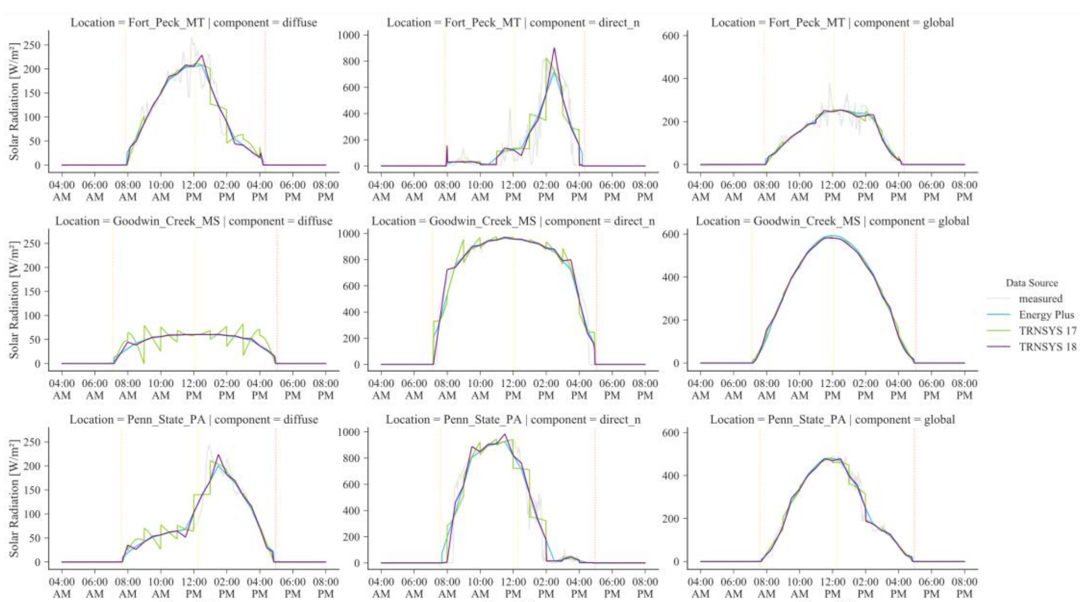

Figure 7 BPS Output and Measured Data for January 4th. Vertical lines illustrate the sunup and sundown time calculated with the NREL SPA algorithm.

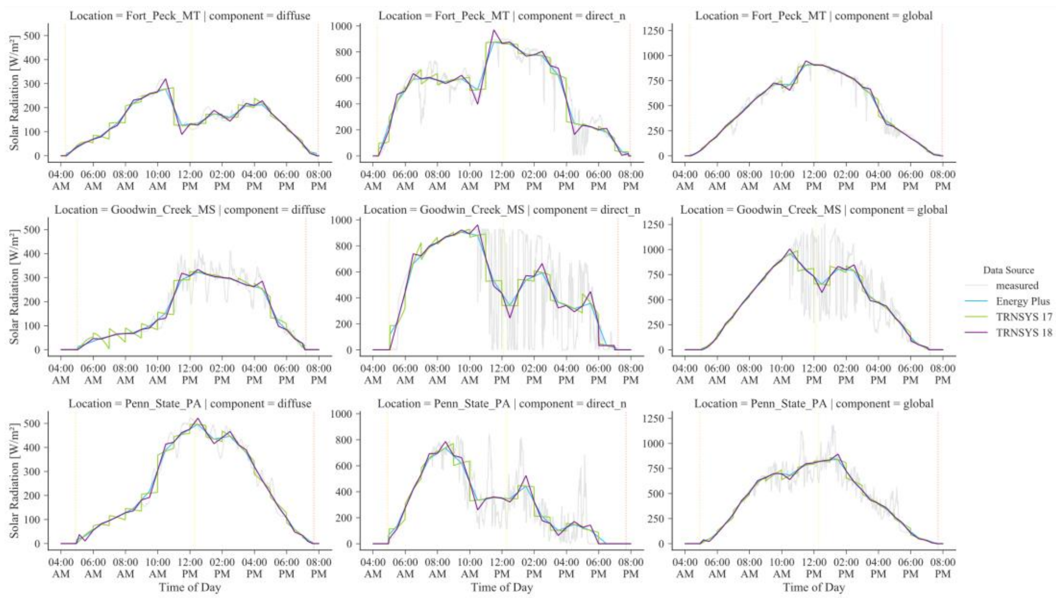

Figure 8 BPS Output and Measured Data for July 16th. Vertical lines illustrate the sunup and sundown time calculated with the NREL SPA algorithm.

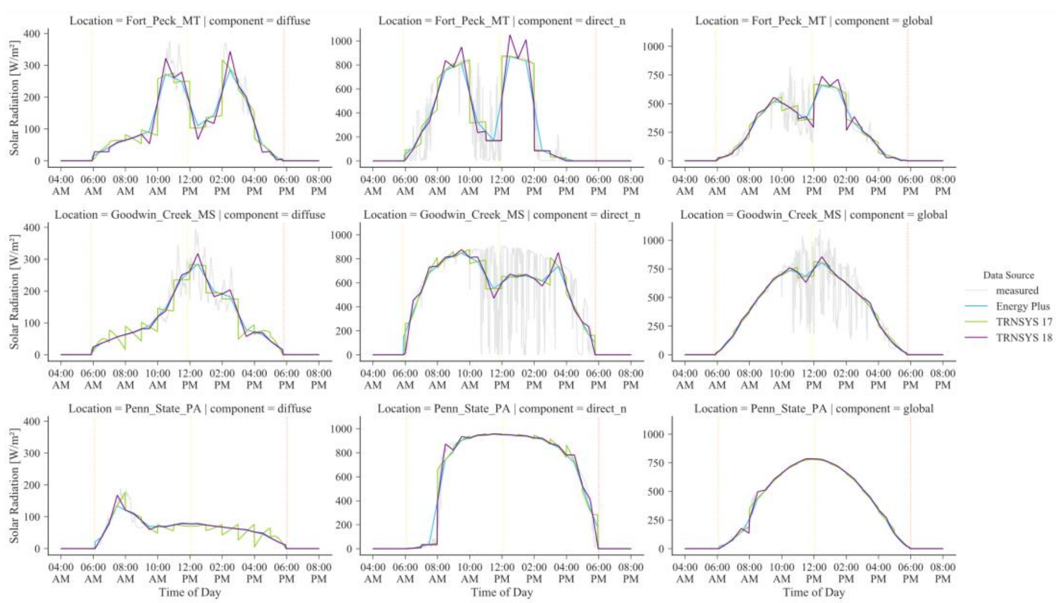

Figure 8 BPS Output and Measured Data for September 27th. Vertical lines illustrate the sunup and sundown time calculated with the NREL SPA algorithm.

Table 3 Hourly integration of solar radiation components centered on the measured values. Data for July 16th at the Fort Peck location is shown

Hour of Day	Diffuse				Direct Normal				Global			
	Energy Plus	TRNSYS 17	TRNSYS 18	measured	Energy Plus	TRNSYS 17	TRNSYS 18	measured	Energy Plus	TRNSYS 17	TRNSYS 18	measured
	-	-	-	Ref [W/m^2]	-	-	-	Ref [W/m^2]	-	-	-	Ref [W/m^2]
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0
4	1.08	1.12	1.00	12.4	1.33	1.00	1.00	64.9	1.16	1.00	0.97	17.0
5	0.98	1.01	1.00	54.2	0.95	1.00	1.00	411.6	1.00	1.00	1.00	130.7
6	1.03	0.94	1.00	84.1	0.96	1.00	1.00	590.1	1.03	1.00	1.01	280.4
7	1.04	1.02	1.00	134.6	0.99	1.00	1.00	596.9	1.01	1.00	0.99	433.6
8	0.97	0.99	1.00	219.3	1.01	1.00	1.00	570.2	1.01	1.00	1.00	579.7
9	0.99	1.00	1.00	255.4	0.98	1.00	1.00	593.6	0.99	1.00	1.00	702.3
10	0.92	1.00	1.00	277.7	1.11	1.00	1.00	509.6	1.04	1.00	1.00	704.6
11	1.15	0.99	1.00	127.9	0.95	1.00	1.00	875.5	0.98	1.00	1.00	899.4
12	1.03	0.99	1.00	135.5	0.99	1.00	1.00	860.7	1.00	1.00	1.00	898.2
13	0.96	0.99	1.00	175.2	1.01	1.00	1.00	783.7	1.01	1.00	1.00	839.7
14	1.05	0.99	1.00	159.7	0.98	1.00	1.00	770.9	1.00	1.00	1.00	755.4
15	0.98	1.00	1.00	207.1	0.95	1.00	1.00	620.8	0.97	1.00	1.00	618.6
16	0.96	1.03	1.00	212.1	1.16	1.00	1.00	250.5	1.03	1.00	0.99	349.9
17	0.99	0.98	1.00	149.8	0.99	1.00	1.00	223.0	1.01	1.00	1.01	229.8
18	0.99	1.01	1.00	84.6	0.92	1.00	1.00	183.5	0.96	1.00	0.99	125.7
19	1.31	1.05	1.00	15.7	1.44	1.00	1.00	28.7	1.33	1.00	1.00	18.4
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean	0.996	0.998	1.000		1.000	1.000	1.000		1.004	1.000	0.999	

Table 4 Mean annual errors in solar radiation due to interpolation techniques from hourly data

Component		Diffuse		Direct normal		Global	
Model		MBE (%)	RMSE (%)	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Location	Software						
Penn State, PA, N = 256,178							
	Reference (W/m^2)	152.7		268.7		308.5	
	EnergyPlus	0.448	22.7	0.637	80.9	0.704	60.8
	TRNSYS 17	-0.194	24.1	-0.020	83.0	-0.005	61.5
	TRNSYS 18	0.036	22.1	-0.051	78.9	0.052	60.2
Fort Peck, MT, N = 253,657							
	Reference (W/m^2)	131.4		346.7		310.1	
	EnergyPlus	0.453	26.9	0.604	94.2	0.671	66.7
	TRNSYS 17	-0.133	28.0	-0.008	96.6	0.032	67.4
	TRNSYS 18	0.052	26.3	-0.175	92.0	0.004	65.8
Goodwin Creek, MS, N = 207,775							
	Reference (W/m^2)	151.7		329.9		348.5	
	EnergyPlus	0.497	22.1	0.833	93.2	0.901	56.4
	TRNSYS 17	-0.155	23.5	0.015	95.8	0.048	56.5
	TRNSYS 18	0.065	21.5	-0.113	91.1	0.058	55.4