TYPE 551: PHOTOVOLTAIC ARRAY SHADING

General Description

It is known that even partial shading of photovoltaics (PV) can have a dramatic effect upon array performance. However, the relationship between the shaded area of a photovoltaic array and the drop in electrical performance due to that shaded area is not only highly non-linear but depends upon the placement of the array with regards to surrounding objects and upon the array's inter and intra modular electrical connections. In order to accurately perform a shading analysis of a photovoltaic array, information about the specific order in which modules are connected in series in parallel, as well as some method for determining time dependent shadow patterns on the array are needed. Only in very rare circumstances would a user have access to such information. As an alternative, component Type551 has been developed as a simplified method for bracketing the effect of shading. Users are asked to select between two general array configurations: generally horizontal rows or generally vertical rows. The first configuration would be appropriate for a series of ballasted roof pan photovoltaics on a flat or sloped roof. The second would be appropriate in a high rise building in which PV is used as a window shading device.

The Type assumes that the array is divided into a user specified number of equal length rows and that all rows in the array are identically sloped. Based on configuration parameters and current input values, the component outputs two different estimates of radiation incident on the array rows. In the more conservative of the two estimates, a row that is partially shaded from beam radiation is assumed to "see" only diffuse radiation. In the less conservative estimate, the fraction of the array exposed to beam radiation is computed and the entire array is assumed to be exposed evenly to that reduced amount.

Nomenclature

$\theta_{z,CollAzimuth}$	[degrees]	The solar zenith angle in the plane of the collector azimuth.
$\Delta\gamma$	[degrees]	The difference between the solar azimuth and collector azimuth angles
θ_z	[degrees]	The solar zenith angle.
ShadedDiffuseRadiation	[kJ/hr]	The amount of diffuse radiation falling on a shaded (non front or non top) row of modules.
UnshadedDiffuseRadiation	[kJ/hr]	The amount of diffuse radiation falling on an unshaded (front or top) row of modules.
VF_{sky}	[0..1]	The fraction of the sky visible from the base of a non-front row of modules in a horizontally oriented array.
VF_{OC}	[0..1]	The fraction of the sky visible from the base of the front row of modules in a horizontally oriented array.
β_{slope}	[degrees]	The slope of the a row of modules, with respect to the horizontal in a horizontally oriented array.
VF_{OA}	[0..1]	The fraction of sky invisible from a non-front row of modules because of a the row in front in a horizontally oriented array.
θ_1	[degrees]	The angle formed between the horizontal and the top of a row of modules as seen from the base of the row directly behind in a horizontally oriented array or the angle formed between the vertical and the bottom of a row of modules as seen from the top of the row directly beneath in a vertically oriented array.
VF_{OB}	[0..1]	The fraction of sky visible from the base of the front row of modules when the modules are oriented vertically (for example as window awnings)
β_{wall}	[degrees]	The slope of the wall when modules are arranged vertically.
VF_O	[0..1]	The fraction of sky that is invisible from a non-top row of modules because of the row above in a vertically oriented array.

		of the row above in a vertically oriented array.
ShadedBeamRadiation	[kJ/hr]	The amount of beam radiation falling on a shaded (non front or non top) row of modules.
UnshadedBeamRadiation	[kJ/hr]	The amount of beam radiation falling on an unshaded (front or top) row of modules.
FCLB	[0..1]	The fraction of a non front or non top row that is exposed to beam radiation.
RowWidth	[m]	The width of each row in the array.
A	[m^2]	The area directly beneath a row. In other words, the area of the array projected onto the horizontal plane.
HH	[m]	The height of a row, projected onto the horizontal.
A_s	[m^2]	The shaded area directly beneath a row (projected onto the horizontal plane)
$XL1,\ XL3, DHor$	[m]	Lengths used in computing shaded and projected areas.
RowSepSolAz	[degrees]	The distance between two rows in the plane of the solar azimuth.
δ, γ, α	[degrees]	Angles defining the Law of Sines
BC, AC, AB	[length]	Lengths defining the Law of Sines
θ_2	[degrees]	The angle between the wall slope and the line connecting the base of one row with the tip of the row above in a vertically oriented array.
α_s	[degrees]	The altitude angle of the sun in the plane of the collector field azimuth

Detailed Description

1. Array Configuration

This component offers the user two choices in general array configuration as shown in Figure 1 below.

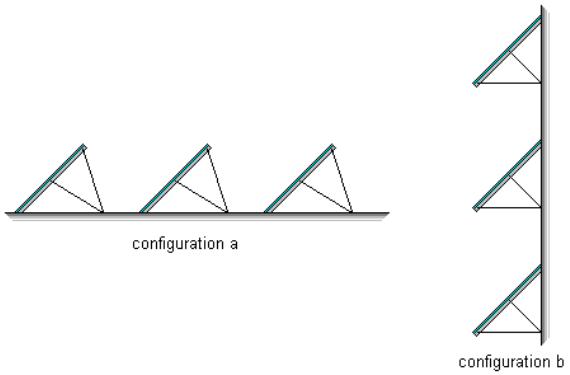


Figure 1: General Photovoltaic Array Configurations

In both configurations, the array is assumed to be broken up into N rows of equal width. These N rows are furthermore assumed to be arranged into a rectangular field as seen from above. It should be noted that the slope of the field on which the rows are arranged does not have to be perfectly horizontal or vertical but can be sloped as shown in Figure 2.

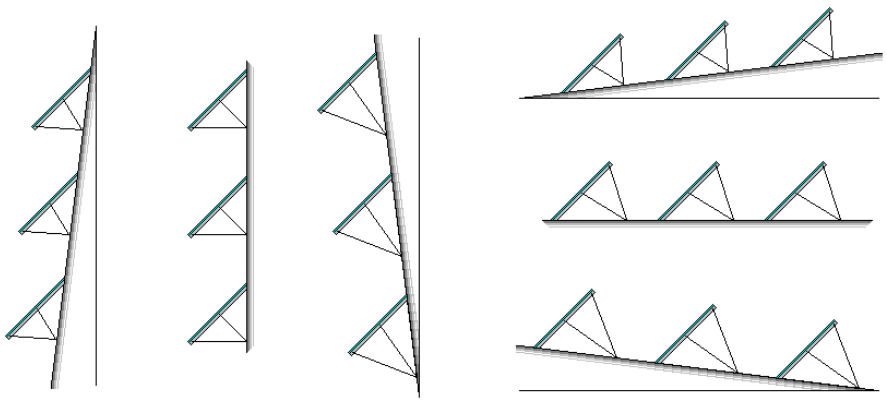


Figure 2: Field Slope Options for Generally Horizontal and Generally Vertical Array Configurations

2. Shading and Photovoltaics

The electrical effect of partially shading a photovoltaic module is difficult to quantify in a general manner because the effect is heavily tied to the placement of surrounding objects, to the way in which the array is configured (whether in rows or all in one plane), to the pattern in which one module is connected to the next, to the photovoltaic technology used, to the way in which individual cells are connected within a single module and to the precautions that the array installer has taken to install bypass diodes.

To illustrate, a photovoltaic can be thought of as a voltage source whose output drops to zero when an opaque cover is placed over the module. If two such voltage sources are placed in series and both are subject to the same light source, then the total voltage output of the combination is twice that of a single module. If however, one of the two modules is covered then its output drops to zero and it acts as an open circuit. The overall voltage of the two modules also drops to zero as current cannot flow through the open circuit. To alleviate the problem, a manufacturer can place a bypass diode across each module so that the current has an alternate path to follow, should one of the modules be operating in open circuit. When two modules are connected in parallel, the overall current is twice that of a single module and the voltage across each parallel branch is equal. Thus if one module is covered and its voltage drops to zero then the voltage of the uncovered module must also drop to zero. Physically the power generated by the uncovered module is dissipated (as heat) in the covered module. Again bypass diodes may be used to mitigate the effect.

Thus far, photovoltaic modules have been used to illustrate the issues of protecting an array against the effects of shading. However, monocrystalline photovoltaic modules are in reality a set of individual photovoltaic cells connected in series and parallel to obtain the desired current voltage characteristic from a module. The above issue of installing bypass diodes is relevant not only at the module level but also at the cell level. This is not necessarily the case for other photovoltaic technologies such as polycrystalline or thin films which do not have a clearly defined structure of electrically connected cells.

The problem is further complicated by the fact that only rarely is one module subject to zero solar radiation while another is in full sun; more often modules are partially shaded, subject perhaps to diffuse radiation but shaded from beam radiation.

3. Shading Estimates

In an effort to bracket the possible response of a photovoltaic array to shaded conditions, this Type makes two estimates of the amount of solar radiation incident on a shaded photovoltaic module, one more conservative than the other. Figure 3 below shows a PV module, all of which is subject to diffuse radiation but only the upper portion of which is subject to beam radiation; in other words a shadow is cast on the PV module.

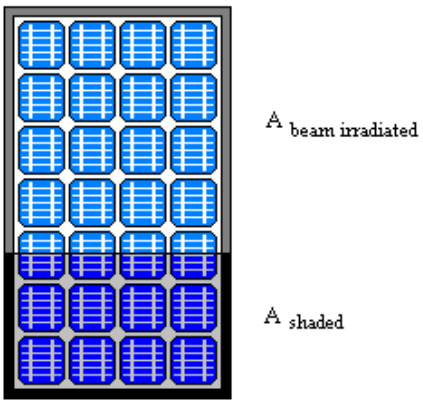


Figure 3: A Partially Shaded Photovoltaic Module

Using the less conservative approach, the area of a module exposed to beam radiation ($A_{beam\ irradiated}$) is computed and the beam radiation falling on that fraction is averaged over the entire area of the module. This assumption will provide the user with a linear shading effect and should corresponds to the case in which the PV installer has used bypass diodes wherever possible to reduce the effect of shading. The less conservative approach should also be used with arrays made up of thin film and polycrystalline photovoltaic panels.

In the more conservative approach, as soon as a portion of the photovoltaic module is shaded from beam radiation, the module is assumed to be completely shaded from beam radiation. In this case the module will still be exposed to diffuse radiation.

4. Solution Methods

The Type551 solution method is based largely on the solution method in Type30, a standard TRNSYS component that performs shading analysis of either flat plate or concentrating thermal collectors [1] [2].

The Type breaks the total amount of radiation falling on a surface into two component parts: diffuse and beam radiation, each of which is treated separately. The Type ignores radiation that may be reflected onto the rows from the ground separating the rows. The following three figures define a number of dimensions and angles that are used in the Type's calculations.

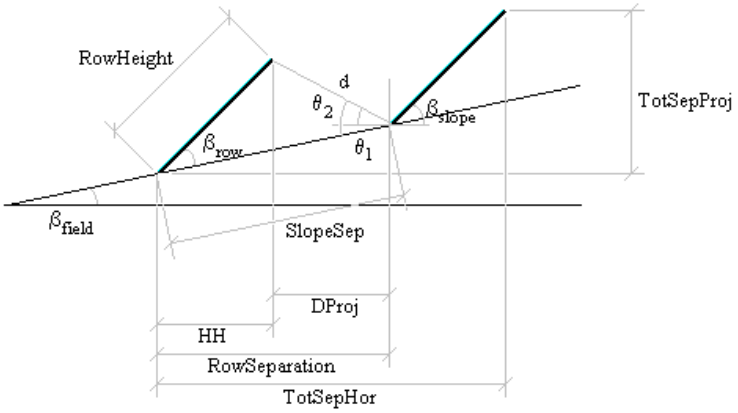


Figure 4: Generally Horizontal Array Dimensions in Elevation View

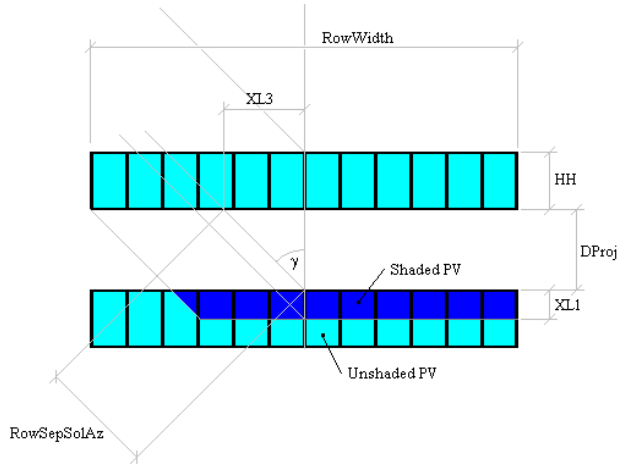


Figure 5: Generally Horizontal Array Dimensions in Plan View

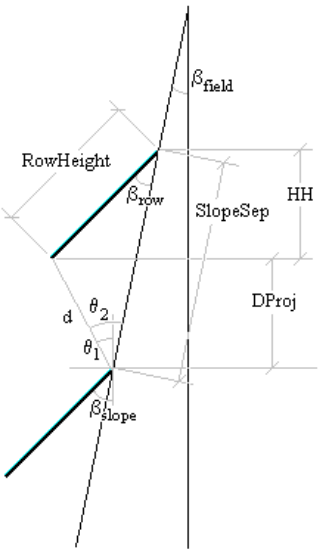


Figure 6: Generally Vertical Array Dimensions in Elevation View

Before any calculations of shaded radiation can take place it is necessary to correct for the fact that the plane of the solar azimuth and the plane of the collector azimuth are not the same. The zenith angle and solar altitude angle in the plane of the collector azimuth must be computed. Normally the solar zenith angle θ_z in Figure 7 is defined as "the angle between the vertical and the line of the sun" [3]. In the same figure, the light gray axis lines define the azimuth of the collector array. These array axis lines are turned by an angle $\Delta\gamma$ from the main East West axis lines.

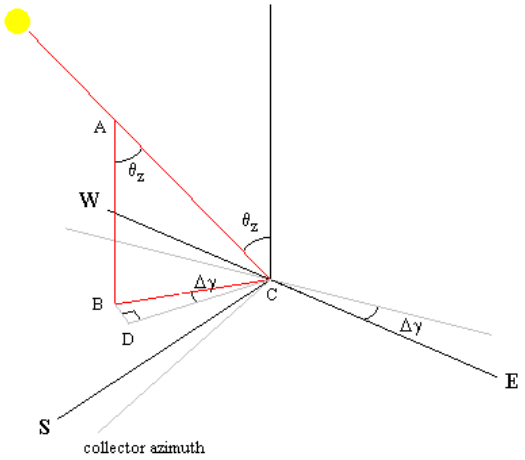


Figure 7: Angles for Calculating the Zenith Angle in the Plane of the Array Azimuth

Based on Figure 7, one can define a line CD that is turned by the same angle $\Delta\gamma$ from the sun line CB. The zenith angle in the plane of the sun line CD is the compliment of angle ACD. In equation form it is:

$$\theta_{z,CollAzimuth} = \tan^{-1}\frac{\cos(\Delta\gamma)\sin(\theta_z)}{\cos(\theta_z)} \qquad \text{(Eq. 551.1)}$$

The amount of diffuse radiation falling on a shaded row of modules is computed as follows:

$$ShadedDiffuseRadiation = UnshadedDiffuseRadiation * VF_{sky} \qquad \text{(Eq. 551.2)}$$

where VF_{sky} is the view factor of the sky as seen from the base of a non-front row. The view factor of the sky could equally well be calculated from the center point of a non-front row or from the top of a non-front row. Computing the view factor from the base of the row provides the most conservative estimate of diffuse radiation incident upon shaded rows. Taking a unit circle as shown in Figure 8, and imagining that the line OB defines a PV surface:

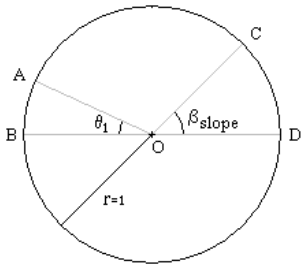


Figure 8: Unit Circle for Horizontal Array Sky View Factor Calculations

The sky view factor seen by the surface OC at point O is:

$$VF_{OC} = \frac{1+\cos(\beta_{slope})}{2} \qquad \text{(Eq. 551.3)}$$

The amount of sky hidden from the point O by the same surface (OC) is 1-VF_{OC}.

Imagine next that the point A marks the top of the row of modules in front of the row described by OC. The amount of sky hidden from the point O by the surface (OA) is 1-VF_{OA} where:

$$VF_{OA} = \frac{1+\cos(\theta_1)}{2} \qquad \text{(Eq. 551.4)}$$

The sky view factor of point O, taking into account the amount of sky that is hidden both by OC and by OA can be written as:

$$VF_O = VF_{OC} - (1 - VF_{OA}) \quad \text{or} \quad VF_O = \frac{1+\cos(\beta_{slope})}{2} - \frac{1-\cos(\theta_1)}{2} \qquad \text{(Eq. 551.5)}$$

For the generally vertical case, Figure 8 is rotated to obtain Figure 9:

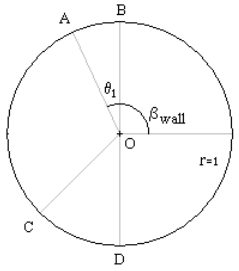


Figure 9: Unit Circle for Vertical Array Sky View Factor Calculations

The surface of a row of modules is again defined by OC and the point A is the unsupported edge of the row of modules above OC. Allowing for the wall defined by OB to be non vertical, the sky view factor of point O is now:

$$VF_{OB} = \frac{1+\cos(\beta_{wall})}{2} \qquad \text{(Eq. 551.6)}$$

and the amount of sky occluded by OA is 1-VF_{OA} or:

$$VF_O = \frac{1-\cos(\theta_1)}{2} \qquad \text{(Eq. 551.7)}$$

The calculation of beam radiation proceeds in much the same manner. The overall equation is

$$ShadedBeamRadiation = UnshadedBeamRadiation * FCLB \qquad \text{(Eq. 551.8)}$$

where FCLB is a dimensionless value between 0 and 1 that indicates the fraction of a non-front row that is exposed to beam radiation. In the more conservative approach to beam radiation, if the value of FCLB is anything less than 1.0, its value is automatically set to 0.0.

Two special case scenarios are checked in the calculation of FCLB for the generally horizontal case; if the sun has risen high enough in the sky, then all rows are completely exposed to beam radiation and FCLB is equal to 1.0. Additionally, it may be that the rows of modules are separated by a distance such that they are entirely exposed to beam radiation not from above but from one side or the other, especially when the sun is just rising or setting. Again, FCLB is equal to 1.0 in this case. At times when neither of the two special cases applies, the fraction of non-front rows exposed to beam radiation is computed by projecting various areas on to a horizontal plane. The area directly beneath the row is calculated as

$$A = HH * RowWidth \qquad \text{(Eq. 551.9)}$$

The shaded collector area as projected onto the horizontal plane is:

$$A_s = XL1 * RowWidth - \frac{(DHor + XL1) * XL3 - DHor * RowSepSolAz * \cos(90 - \gamma)}{2} \qquad \text{(Eq. 551.10)}$$

where the final term accounts for the beam irradiated area on the end of an otherwise shaded row as shown in figure 4b. The fraction of exposed area is then:

$$FCLB = 1 - \frac{A_s}{A} \qquad \text{(Eq. 551.11)}$$

For a generally vertical array, two special cases are checked as well. First it is checked whether the sun has risen high enough in the sky that it is entirely hidden from the modules by the building itself as shown in Figure 10.

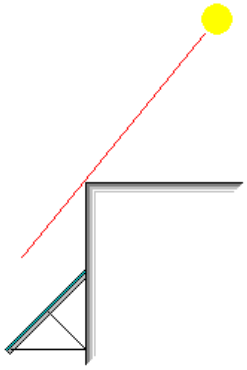


Figure 10: Modules are Entirely Shaded from beam Radiation

Because no information about how high the generally vertical plane extends above the top row of modules, the check is actually made on whether the solar altitude angle is greater than wall slope angle.

The second special case is that as long as the solar altitude angle is less than the compliment of angle θ_1 in Figure 5, then all rows of the array are entirely exposed to beam radiation and FCLB is equal to 1.0. If

neither special case is true, then the length of a module that is beam irradiated (BC in Figure 11 below) is calculated.

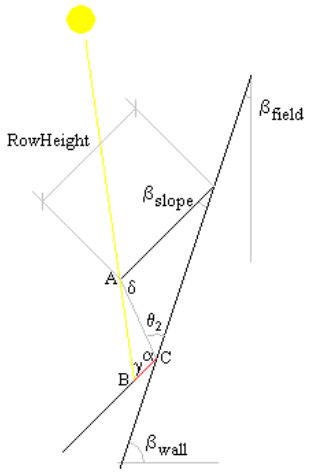


Figure 11: The Length of a Generally Vertically Oriented Row that is Beam Irradiated.

BC in Figure 11 above is computed using the law of sines on triangle ABC, which states that:

$$\frac{\sin(\delta)}{BC} = \frac{\sin(\gamma)}{AC} = \frac{\sin(\alpha)}{AB} \qquad \text{(Eq. 551.12)}$$

Based on a number of known angles, the length BC can be written as:

$$BC = \frac{AC\sin(\theta_2 + \beta_{wall} + \alpha_s - 180)}{\sin(180 + \beta_{slope} - \beta_{wall} - \alpha_s)} \qquad \text{(Eq. 551.13)}$$

The distance AC has already been calculated; it is the distance d from Figure 6. β_{wall} is the slope of the wall, β_{slope} is the angle between an array row and the wall, and α_s is the altitude angle of the sun in the plane of the collector field azimuth.

The area defined by BC*RowWidth is corrected for any beam radiation that strikes the end of the array rows as shown in Figure 12.

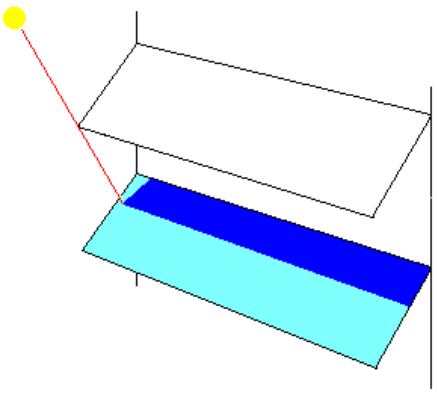


Figure 12: Beam Irradiation from the Side

References

[1] Klein, S.A. et al., TRNSYS 15.x Reference Manual, Solar Energy Laboratory, University of Wisconsin – Madison, March 2000

[2]

[3] Duffie, J.A. and W.A. Beckman, Solar Engineering of Thermal Processes. Second edition, New York: John Wiley and Sons, Inc., 1991