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# Solar Collectors and Photovoltaic

# in energyPRO

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## 1. Introduction

In energyPRO you do of course have the possibility to model a solar collector or a photovoltaic as a user defined unit, by entering your own formulas correlating the external conditions (e.g. solar radiation and ambient temperature) to the productions. But the formulas are quite complex, therefore we offer in energyPRO models of a solar collector unit and a photovoltaic unit, including array shading. Setting up the units is based on time series with solar radiation and ambient temperature, information about location, orientation and performance (found in datasheets from the manufacturer). In energyPRO 4.2 we have included a more accurate calculation of the true solar time.

## 2. User interface



The units are added to a project by right clicking the folder Energy Conversion Units:

## 2.1 Flat plate solar collector and evacuated tube solar collector

The window for the flat plate solar collector has the following appearance:

🧰 Solar Collector	
Name: Solar Collector	
Size and Position	Non availability periods
Total area of collectors 1000 m <sup>2</sup>	
Inclination of solar collector 35 degree	
Orientation of solar collector	
(Deviation from South)	
Select Input Time Series	Collector specification
Ambient temperatures Hourly outdoor ter	Start efficiency (ŋo) 0,81500
Radiation on horizontal plane	Loss coefficient (a1) 2,43000 W/(m <sup>2</sup> °C)
Aggregated Radiation	Loss coefficient (a2) 0,01200 W/(m <sup>2</sup> °C) <sup>2</sup>
<ul> <li>Direct and Diffuse Radiation</li> </ul>	Incidence angle modifier
Aggregated radiation Aggregated solar r	© Coefficient 4,00000 As
	$\bigcirc$ K <sup><math>\theta</math></sup> at 50 degree 0,95272 graphics
Collector field specifications	
Temperatures on collector 🔄 side of heat excl	nanger Temperature drop over heat exchanger 0,00 °C
From collector <constant></constant>	90,00 °C Losses in pipes in collector field in
To collector <constant></constant>	10.00 °C percentage of production 0 %
✓ Include effects of array shading	
Number of rows 10 Distance rows	e between 4,50 m Height, units 2,27 m
Inclination, ground 0 degree 0 (Deviation)	tion of ground ion from south)
The collector specifications are valid for an Arcon HT s	olar collector.
	OK Cancel

There is four groups of information: size and position of the solar collector, input time series, collector specification and collector field specifications.

**The size and position of the collectors** includes three input fields. Total area of collectors has to be in square meters. It is important that the collector area match the area used when determining the values in the collector specification. Typically, efficiency curves are provided for gross area in the US and aperture area in Europe.

The inclination of the solar collector is measured from horizontal:

Inclination

The orientation of the solar collector has the value 0 degrees when the collector faces due south. West is positive, while east is negative.

**The input time series** includes a time series with ambient temperatures. For more accurate results you should use a time series with at least hourly values.

The solar radiation on horizontal plane can be one time series with aggregated values or be two separate time series with direct radiation and diffuse radiation, respectively.

The time series has to be included as time series under External conditions.

Information to be entered in the fields in the **collector specification** has to be delivered by the manufacture of the collectors. For detailed information on the values, please look into section 3.

For the flat plate solar collector, the incidence angle modifier can either be defined by a coefficient or as its value at an incidence angle of 50 degrees. In both cases the resulting incidence angle modifier can be seen graphical.

For the evacuated tube solar collector the input to the incidence angle modifier looks like this:

Evacuated tube collectors are optically non-symmetric. The incidence angle modifier is divided into a longitude and transversal IAM. The above values look like this as graphic:



In the **collector field specifications** the temperatures of the fluid are set. The temperature from and to the collectors can either be fixed values or you can select a time series.

Most often, the user knows the temperatures on the demand side of the heat exchanger, but energyPRO needs to know the values on the production side of the heat exchanger. The user can select whether to set the temperatures on the solar side of the heat exchanger or on the demand side of the heat exchanger. Therefore, we include a parameter,  $t_{hx}$  regarding the temperature drop over the heat exchanger if the user selects the demand side of the heat exchanger. The average temperature of the collectors,  $t_m$  is then calculated as follows:

 $t_m = (t_{from} + t_{to})/2 + t_{hx}$ 

In large collector fields the loss from piping can matter. Losses in pipes in collector field in percentage of production can be specified.

## 2.2 Photovoltaic

This is the window for the photovoltaic production unit:

🦲 Solar photovoltaic		_ 🗆 🔀
Name: Solar photovoltaic		
Size and Position	Non availability periods	
Installed capacity 500,0 kW 🔄		
Inclination of photovoltaic 35 degree Orientation of photovoltaic (Deviation from South) degree		
Select Input Time Series	PV module specification	
Ambient temperatures Hourly outdoor ter	Maximum power	100 W
Radiation on horizontal plane	Temperature coefficient	0,400 %/°C
Aggregated Radiation	NOCT	45 °C
<ul> <li>Direct and Diffuse Radiation</li> </ul>	Miscellaneous	
Aggregated radiation Aggregated solar r	Aggregated Losses from module to grid	10,0 %
	Number of PV modules	5000
Include effects of array shading		
Comments:		
		OK Cancel

There is three groups of information: size and position of the photovoltaic, input time series and photovoltaic specification.

The first two groups are very similar to the solar collector. The only difference is that for photovoltaic the installed capacity is measured not in  $m^2$  but in kW or MW.

Information to be entered in the fields in the **PV module specification** has to be delivered by the manufacture of the photovoltaics. For detailed information on the values, please look into section 3.

## 2.3 Location on Time series

For correct calculation of the angle of incidence of beam radiation on the inclined surface and correct correlation between the angle of incidence and the solar radiation, it is important that the location of the time series is specified correct.

🦲 Aggreg	📮 Aggregated solar radiation, horisontal, London 📃 🗖 🔀							
Name: A	Name: Aggregated solar radiation, horisont							
Develop	Development of time series in Planning period							
Time	series	51						
0	SolarHe	vicontal						
Sym	IDOI SUAINO	insontai						
Unit	W/m2							
#	Date 🛛 🕹	SolarHorisontal [W/m2]	Copy all					
1	01-01-2007 00:00:00	0,0000	# Comy solocted					
2	01-01-2007 08:00:00	15,0000	Copy selected					
3	01-01-2007 09:00:00	53,0000	Paste					
4	01-01-2007 10:00:00	94,0000	Delete all					
5	01-01-2007 11:00:00	163,0000						
6	01-01-2007 12:00:00	174,0000	Delete selected					
7	01-01-2007 13:00:00	102,0000	As graphics					
8	01-01-2007 14:00:00	51,0000	Time series is in deutisht series time					
9	01-01-2007 15:00:00	25,0000	I'me series is in daylight saving time					
10	01-01-2007 16:00:00	0,0000	✓ Define location					
11	02-01-2007 08:00:00	8,0000	Latitude 51,500					
12	02-01-2007 09:00:00	31,0000	Longitude 0,000					
13	02-01-2007 10:00:00	10,0000	Different time zene					
14	02-01-2007 11:00:00	51,0000						
15	02-01-2007 12:00:00	43,0000	M					
		Dalata Kara						
	Add line Delete line							
Deve	Developing over the years As graphics							
Commen	Comments:							
			OK Cancel					

This is set in the time series with the solar radiation:

If location is not defined, you will have an error warning. The latitude and longitude are specified in decimal degrees. The latitude has positive values north of equator and negative values south of equator. The longitude has positive values east of Greenwich Mean Time and negative values west of Greenwich Mean Time.

Most often solar radiation data is in standard time. However, should it be in daylight saving time, it is important to check the setting "Time series is in daylight saving time" for correct calculation of the solar radiation onto the inclined surface.

## 2.4 Array shading

The calculated radiation on an inclined surface is valid for single rows of surface. Often, large scale solar collector or photo voltaic systems will be mounted on the ground in rows. The radiation will be reduced on the subsequent rows. Enabling Include effects of array shading will take that into account.

✓ Include effects of an	ray shading				
Number of rows	10	Distance between rows	4,50 m	Height, units	2,27 m
Inclination, ground	0 degree	Orientation of ground (Deviation from south)	0 degree		

The number of rows is used for calculating the ratio between the first unshaded row and the subsequent rows. The distance between the rows,  $d_r$  and the height of the collector, h, determines together with the position of the sun the shadow on the subsequent rows.

Inclination and orientation of the ground can also be included.



## 3. Method of calculation

## 3.1 Definitions

α	[°]	Solar altitude angle (90° - $\theta_z$ )
φ	[°]	Latitude
δ	[°]	Solar declination angle
γ	[°]	Orientation of inclined plane, south = $0^\circ$ , west = $90^\circ$
γ <sub>t</sub>	Π	Temperature coefficient for photovoltaic module efficiency
θ	[9]	Angle of incidence of beam radiation on inclined plane
θ.	[0]	Longitudinal angle of incidence of beam radiation on inclined plane
e,	[0]	Transversal angle of incidence of beam radiation on inclined plane
0 <sub>t</sub>	[ ] [°]	Hour angle
0		Paflaction factor
ρ		Selen zenith angle
$\Theta_z$		Solar zeniti angle
$\lambda_{ m misc}$		Losses from the photovoltaic-module to the grid
a	$\begin{bmatrix} \\ \\ \end{bmatrix}$	Incidence angle modifier coefficient
A		l otal solar collector area
A <sub>I</sub>		Anisotropy index
I	$\begin{bmatrix} \\ \end{bmatrix}$	Modulating factor
I T	[W/m]	I otal radiation on a norizontal plane
I <sub>b</sub>	[W/m]	Beam radiation on a horizontal plane
I <sub>d</sub>	[W/m]	Diffuse radiation on a norizontal plane
I <sub>diff</sub>	[W/m]	Diffuse radiation on an inclined plane
I <sub>dir</sub>	[W/III]	Extractamentation on an inclined plane
I <sub>0</sub> I	[W/III]	Extraterrestrial radiation on a nonizolitad plane
I <sub>ref</sub>	[W/III]	Total rediction on an inclined plane
I <sub>s</sub> I	[W/III2]	Fold radiation on an inclined plane $S_{alar}$ solution of an inclined plane
I <sub>sc</sub>	[W/III2]	Solar constant, 1507 W/III
I <sub>bn</sub>	[W/III2]	Extratorrestrial radiation at normal incidence
I <sub>on</sub> I	$[W/m^2]$	Extra terrestrial radiation at normal incluence <b>P</b> adjation at standard conditions (1000 $W/m^2$ ) (photovoltaic)
I <sub>STC</sub>	[ <b>vv</b> / III ] []	Incidence angle modifier
$\mathbf{K}_{\theta}$		Incluence angle modifier
$\mathbf{K}_{\theta}(\theta_{l})$		
$\mathbf{K}_{\theta}(\boldsymbol{\theta}_{t})$		Transversal incidence angle modifier
$a_1$	$[W/(m^2 °C)]$	First-order coefficient in collector efficiency equation
a <sub>2</sub>	$[W/(m^2 °C^2)]$	Second-order coefficient in collector efficiency equation
K <sub>T</sub>		Ratio of total radiation on a horizontal plane to extraterrestrial radiation
n		Day of year
n <sub>0</sub>		Intercept (maximum) of the collector efficiency
NOCT	[°C]	Nominal Operating Cell Temperature (photovoltaic)
P <sub>pv</sub>	[W]	Electricity production from a Photovoltaic module
P <sub>max</sub>	[W]	Installed capacity, photovoltaic
P <sub>elec</sub>		Electricity production to the grid from the photovoltaic plant
R <sub>b</sub>		Ratio of beam radiation on an inclined plane to beam on horizontal
R <sub>d</sub>		Ratio of diffuse radiation on an inclined plane to diffuse on horizontal
<b>K</b> <sub>r</sub>	IJ	Ratio of reflected radiation on an inclined plane to total radiation on horizontal
S	[°]	Inclination of surface
t.	[°C]	Ambient temperature
•a t	[°C]	Solar collectors average temperature
۲m	[ ]	sona concetors average temperature

$T_{cell}$	[°C]	Photovoltaic operation cell temperature
T <sub>STC</sub>	[°C]	The cell temperature at standard conditions (25 °C) (photovoltaic)
T <sub>TST</sub>	h]	True Solar Time
Tz	[h]	Zone time or local time
Tj	[h]	Equation of time
Κ	[°]	Local Constant
Cor <sub>DST</sub>	[h]	Correction for daylight saving time

## **3.2 External conditions**

In energyPRO external time series are needed to calculate the solar radiation on an inclined plane. These time series include solar radiation. Optimally, the solar radiation is divided into beam radiation,  $I_b$  and diffuse radiation,  $I_d$ . Alternatively, the solar radiation comes as total radiation, I.

If the solar radiation comes as total radiation the diffuse and the beam radiation can be calculated as follows (Reindl, D.T, et al., "Diffuse Fraction Correlations" Solar Energy, vol. 31, No 5, October 1990):

Interval: $0 \le K_T \le 0,3$	Constraint: $I_d/I \le 1,0$	$I_d / I = 1,020 - 0,254 * K_T + 0,0123 * \sin \alpha$
Interval: $0,3 < K_T < 0,78$	Constraint: $0, 1 \le I_d/I \le 0,97$	$I_d / I = 1,400 - 1,749 * K_T + 0,177 * \sin \alpha$
Interval: $0,78 \le K_T$	Constraint: $0, 1 \le I_d/I$	$I_d / I = 0,486 * K_T + 0,182 * \sin \alpha$

Where  $K_T$  is the ratio of total radiation on a horizontal plane to extraterrestrial radiation:

$$K_T = \frac{I}{I_o}$$

I<sub>o</sub> is defined as:

 $I_o = I_{sc} * \cos \theta_z$ 

where  $I_{sc}$  is the solar constant, 1367 w/m<sup>2</sup>  $\theta_z$  is the solar zenith angle, described in section 3.3.1.

The beam radiation is

 $I_b = I - I_d$ 

## 3.3 Radiation on solar collector or photovoltaic

This section describes the calculation of radiation on an unshaded surface. Section 3.4 contains the effects of array shading.

The time series with solar radiation are radiation on horizontal plane. Most often the solar collector or photovoltaic is inclined. Therefore the first task is to convert the radiation on horizontal to the inclined plane.

#### 3.3.1 Beam radiation

The relation between the beam radiation on an inclined plane and the beam radiation on horizontal is giving by the factor  $R_{\rm b}$ 

$$R_b = \frac{\cos\theta}{\cos\theta_z}$$

where  $\theta$  is angle of incidence of beam radiation on inclined plane.

The solar zenith angle is specified by the formula:

 $\cos\theta_z = \sin\delta^*\sin\phi + \cos\delta^*\cos\phi^*\cos\omega$ 

where  $\delta$  is the solar declination angle  $\phi$  is the latitude  $\omega$  is the hour angle

The solar declination angle is approximately specified by:

$$\delta = 23,45 * \sin\left(360 * \frac{284 + n}{365}\right)$$
 (Expressed in degrees)

where n is the day of the year.

The hour angle,  $\omega$ , is defined by:

$$\omega = 15 \frac{degrees}{hour} * (T_{TST} - 12)$$

Where  $T_{TST}$  is True Solar Time. True Solar Time is defined in section 3.3.1.1 below.

The beam radiation angle of incidence on an inclined plane is found by the following formula:

$$\cos \theta = \sin \delta * \sin \phi * \cos s - \sin \delta * \cos \phi * \sin s * \cos \gamma$$
$$+ \cos \delta * \cos \phi * \cos s * \cos \omega$$
$$+ \cos \delta * \sin \phi * \sin s * \cos \gamma * \cos \omega$$
$$+ \cos \delta * \sin s * \sin \gamma * \sin \omega$$

where s is the inclination of the plane  $\gamma$  is the plane's orientation.

The beam radiation on an inclined plane:

 $I_{dir} = I_b * R_b$ 

#### 3.3.1.1 True Solar Time

The converting from local time or Zone time to true solar time is done by:

 $T_{TST} = T_z + T_j + K - Cor_{DST}$ 

Where  $T_z$  is zone time or local time  $T_j$  is the equation of time K is the Local Constant  $Cor_{DST}$  is correction for daylight saving time

The equation of time,  $T_j$ , is the deviation over the year between the local time and the true solar time.  $T_j$  is found by

 $T_i = 229.2 * (0.000075 + 0.001868 * \cos B - 0.030277 * \sin B - 0.014615 * \cos(2B) - 0.04089 * \sin(2B))$ 

Where B is in degrees and found by

 $B = (n-1) * \frac{360}{365}$ 

Where n is number day in year.

 $T_j$  varies from approximately -15 minutes to approximately + 17 minutes.



The Local Constant, K, is found by

 $K = -4 \frac{min}{degree} * (l_m - l_{st}) degree$ 

Where  $l_m$  the standard meridian for the local time zone and  $l_{st}$  is the longitude of the location in question.

The correction,  $Cor_{DST}$  for daylight saving time has the value 1 from start to end of Daylight Saving Time and 0 in the standard time.

The true solar time shall be in the middle of each time step. If the sun rise or set in the time step, the true solar time shall be in the middle from sunrise to end of time step when in the morning and in the middle from start of time step and sunset, when in the evening.

#### 3.3.2 Diffuse radiation

The ratio between the diffuse radiation on an inclined plane and horizontal is given by (Reindl, D.T., Beckman, W.A. and Duffie, J.A., "Evaluation of Hourly Tilted Surface Radiation Models", Solar Energy, Vol. 45, No. 1, (1990), pp. 9-17):

 $R_d = 0.5 * (1 - A_I) * (1 + \cos s) * (1 + (f) * \sin^3(s/2)) + A_I * R_b$ 

Where A<sub>I</sub> is Anisotropy index f is modulating factor

A<sub>I</sub> is defined as follows:

$$A_I = \frac{I_{bn}}{I_{on}}$$

Where I<sub>bn</sub> is beam radiation at normal incidence I<sub>on</sub> is extraterrestrial radiation at normal incidence

f is defined as follows:

$$f = \sqrt{\frac{I_b}{I}}$$

The extraterrestrial radiation at normal incidence is set equal to the Solar Constant.

The beam radiation at normal incidence is found by setting  $\theta = 0$ .

Hereby the diffuse radiation on the inclined plane:

 $I_{diff} = I_d * R_d$ 

### **3.3.3** Reflected radiation

The contribution from radiation reflected from the ground is defined as follows:

$$R_r = 0.5 * (1 - \cos s) * \rho$$

where  $\rho$  is the reflection factor

ρ depends on local conditions, a typical value is 0.2, equal to ground covered by grass.

Hereby the reflected radiation becomes

 $I_{ref} = I * R_r$ 

#### 3.3.4 Total radiation

The total radiation on the inclined surface is the sum of the beam, diffuse and reflected radiation:

 $I_{s} = I_{dir} + I_{diff} + I_{ref}$ 

## 3.4 Array shading

Without Array shading the calculated radiation on an inclined surface is valid for single rows of surface. Often, large scale solar collector or photo voltaic systems will be mounted on the ground in rows. The radiation will be reduced on the subsequent rows.



The reduction of the radiation depends on the following input data or solar data:

•	$\beta_{gr}$	[°]	The inclination of the ground
---	--------------	-----	-------------------------------

- $\gamma_{gr}$  [°] The orientation of the ground related to south
- s [°] The inclination of the surfaces
- $\gamma_{surf}$  [°] The orientation of the surfaces related to south
- h [m] The height of surfaces
- d<sub>r</sub> [m] The distance between the rows related to the ground
- φ [°] The latitude of location
- N<sub>rows</sub> [] The number of rows
- ω [°] The solar hour angle
- $\Theta_z$  [°] The solar zenith angle

#### 3.4.1 Beam radiation

If the inclination of the ground is zero, the surfaces of the solar collectors or PVs are orientated at south and the sun is in south, the length of the shadow can be calculated by the use of sinus relations:

$$l_{s} = h - \frac{d_{r}}{\sin(180 - s - (90 - \theta_{z}))} * \sin(90 - \theta_{z})$$

However, the ground can have any inclination in any direction, the surfaces can have any inclination in any direction and the sun is deviating from south most of the day.

We need to find the length of the shadow on the surface in the hour angle plane,  $\omega$ .

$$l_{s\omega} = h_{\omega} - \frac{d_{r\omega}}{\sin(180 - s'_{\omega} - (90 - (\theta_z - \beta_{gr,\omega})))} * \sin(90 - (\theta_z - \beta_{gr,\omega}))$$

Where

 $l_{s\omega}$  is the length of the shadow on the surface  $h_{\omega}$  is the height of the surface  $d_{r\omega}$  is the distance between the rows  $s'_{\omega}$  is the surface's inclination related to the ground  $\beta_{gr,\omega}$  is the inclination of the ground All in the hour angle plane,  $\omega$ .

The height of the surface in the hour angle,  $h_{\omega}$  is found by the following cosine relation:

$$h_{\omega} = \sqrt{h_{gr\omega}^2 + (\sin s * h)^2 - 2 * h_{gr\omega} * (\sin s * h) * \cos\left(90 - \left(\beta_{gr,surf\omega} - \beta_{gr\omega}\right)\right)}$$

Where  $h_{gr\omega}$  is the height of the surface, when projected down on the ground:

$$h_{gr\omega} = \frac{\cos s * h}{\cos(\beta_{gr,surf\omega} - \beta_{gr\omega}) * \cos \omega}$$

The inclination of the ground in the hour angle,  $\beta_{gr,\omega}$  is found by:

$$\beta_{gr,\omega} = \operatorname{asin}\left(\sin\beta_{gr} * \cos(\omega - \gamma_{gr})\right)$$

The distance between the rows in the hour angle,  $d_{r\omega}$  is found by:

$$d_{r\omega} = \frac{\cos \beta_{gr,surf}}{\cos(\omega - \gamma_{surf}) * \cos \beta_{gr,\omega}} * d_r$$

 $\beta_{gr,surf}$  is the grounds inclination in the orientation of the surfaces:

$$\beta_{gr,surf} = \operatorname{asin}\left(\sin\beta_{gr} * \cos(\gamma_{surf} - \gamma_{gr})\right)$$

The surface's inclination in the hour angle related to the inclination of the ground:

$$s'_{\omega} = \arcsin\left(\frac{\sin(90 - \beta_{gr\omega}) * \sin s * h}{h_{\omega}}\right)$$

The part of the total surface area in shadow, Sh<sub>frac</sub> is calculated as follows

$$Sh_{frac} = \frac{(N_{rows} - 1) * min\left(\frac{l_s}{h_{\omega}}, 1\right)}{N_{rows}}$$

Where N<sub>rows</sub> is the number of rows.

With correction for array shading the beam radiation becomes

$$I_{dir} = I_b * R_b * \left(1 - Sh_{frac}\right)$$

#### **3.4.2** Diffuse radiation

The shadow impact on the diffuse radiation is visualized below:



Where  $S_v$  is the angle of sky view of the rows affected by shading of proceeding row and  $S_{v1}$  is the sky view of the first row, which is not affected by shading, but where the inclination of the ground in the orientation of the surfaces is taking into consideration.

 $S_{v1}$  is equal to  $180 - (s - \beta_{gr, surf})$ 

The ratio between the diffuse radiation on first row and horizontal, R<sub>d1</sub> is given by

$$R_{d1} = 0.5 * (1 - A_I) * (1 + \cos(s - \beta_{gr,surf})) * (1 + (f) * \sin^3(s/2)) + A_I * R_b$$

The ratio between the diffuse radiation on subsequent rows and horizontal,  $R_d$  is given by the average of

$$R_d = 0.5 * (1 - A_I) * (1 + \cos(180 - s_v)) * (1 + (f) * \sin^3(s/2)) + A_I * R_b * (1 - Sh_{\text{frac}})$$

The height of the collector is split in 10 pieces. The  $s_v$  and  $R_d$  is calculated at the middle for each of them and the average  $R_d$  is used.

 $S_v$  is found by the following cosine relation:

$$S_{v} = \arccos\left(\frac{h^{2} + {d'_{r}}^{2} - {d_{r}}^{2}}{2 * h * {d'_{r}}}\right)$$

Where d'<sub>r</sub> is the distance between the bottom of the row and the top of the preceding row.

d'<sub>r</sub> is found by the following cosine relation:

$$d'_{r} = \sqrt{h^{2} + d_{r}^{2} - 2 * h * d_{r} * \cos(s - \beta_{gr,surf})}$$

The resulting  $R_{d,sh}$  becomes

$$R_{d,sh} = \frac{\left((N_{rows} - 1) * R_d + R_{d1}\right)}{N_{rows}}$$

The diffuse radiation on the inclined surface when taking shading into consideration becomes

$$I_{diff} = I_d * R_{d,sh}$$

#### 3.4.3 Reflected radiation

The reflected radiation ratio when taking shading into consideration is divided into the beam,  $R_{r,b}$  and diffuse,  $R_{r,d}$  radiation. Further, the ratio is different for the first,  $R_{r1}$  and the following rows,  $R_{rn}$ . Beam and diffuse reflected radiation on the first rows are given as

$$R_{r1,b} = R_{r1,d} = 0.5 * (1 - \cos(s - \beta_{gr,surf})) * 0.2$$

The reflected radiation on the proceeding rows is calculated as ratio of the reflected radiation on the first row,  $r_{p-1}$ .

The beam reflected radiation on the proceeding rows depends on the length of the beam on the ground,  $l_{sun}$ . The length is zero if the surface is partly in shade, meaning that no beam radiation reach the ground in front of the row.

If the length of the beam on the ground is equal to h,  $r_{p-1,b}$  is set to 1. The length is calculated as follows:

$$l_{sun} = d_{r\omega} - \frac{h_{\omega}}{\sin(90 - \theta'_{z\omega})} * \sin(180 - s'_{\omega} - (90 - \theta'_{z\omega}))$$

And r<sub>p-1,b</sub> becomes

$$r_{p-1,b} = \frac{l_{sun}}{h}$$

 $R_{rn,b} = R_{r1,b} * r_{p-1,b}$ 

The reflected beam radiation, R<sub>r,b</sub> becomes

$$R_{r,b} = \frac{\left((N_{rows} - 1) * R_{rn,b} + R_{r1,b}\right)}{N_{rows}}$$

The reflected diffuse radiation on the proceeding rows as ratio of the reflected diffuse radiation on the first row,  $r_{p-1,d}$  has been defined as follows

$$r_{p-1,d} = \frac{S_v}{\left(180 - (s - \beta_{gr,surf})\right)}$$

The diffuse reflected radiation,  $R_{\text{rn,d}}$  becomes

$$R_{rn,d} = R_{r1,d} * r_{p-1,d}$$

The overall reflected diffuse radiation,  $R_{r,d}$  becomes

$$R_{r,d} = \frac{\left((N_{rows} - 1) * R_{rn,d} + R_{r1,d}\right)}{N_{rows}}$$

The reflected radiation on the inclined surface when taking shading into consideration becomes

 $I_{ref} = I_b * R_{r,b} + I_d * R_{r,d}$ 

## 3.5 Solar Collector

The formula for a solar collector is as follow (without Incidence angle modifier):

$$Y = A * \left( I_s * n_o - a_1 * (t_m - t_a) - a_2 * (t_m - t_a)^2 \right)$$

where

Y:	heat production, [W].
A:	Solar collector area [m <sup>2</sup> ]
I <sub>s</sub> :	Solar radiation on solar collector, $[W/m^2]$
t <sub>m</sub> :	The collectors average temperature, [°C], that is an average between the temperature
	of the cold water entering the collector and the hot water leaving the collector
t <sub>a</sub> :	The ambient temperature, [°C]. For the best results the ambient temperatures should
	be hourly.

The efficiency of the solar collector is defined by three parameters:

- n<sub>o</sub>: Intercept (maximum) of the collector efficiency, [-]
- a<sub>1</sub>: The first-order coefficient in collector efficiency equation,  $[W/(m^2 \circ C)]$
- a<sub>2</sub>: The second-order coefficient in collector efficiency equation,  $[W/(m^2 \circ C^2)]$

Those 3 parameters are available for collectors tested according to ASHRAE standards and rated by SRCC (ASHRAE, 2003; SRCC,1995), as well as for collectors tested according to the recent European Standards on solar collectors (CEN, 2001). Many examples of collector parameters can be found on the internet (e.g. SPF, 2004).

Note: It is important to make sure that collector area entered as a parameter match the area used when determining the values of  $n_0$ ,  $a_1$  and  $a_2$ . Typically, efficiency curves are provided for gross area in the US and aperture area in Europe.

Furthermore, the model includes Incidence Angle Modifier, IAM or  $K_{\theta}$ . The sun is not always located perpendicular to the collector plane; the incidence angle generally changes both during the course of a day and throughout the year. The transmittance of the cover glazing for the collector changes with the incidence angle.



Typically, the Incidence angle modifier for a flat plate solar collector looks as below:

It can also be defined as follow:

$$K_{\theta} = 1 - \tan^{a}(\frac{\theta}{2})$$

where  $\theta$  is the incidence angle on the collector. a is the measured coefficient.

Including  $K_{\theta}$  the formula for the heat production from the solar collector becomes:

$$Y = A * \left( \left( I_{beam} * K_{\theta} + (I_{diffuse}) * K_{60^{\circ}} \right) * n_o - a_1 * (t_m - t_a) - a_2 * (t_m - t_a)^2 \right)$$

The radiation is split into beam radiation and diffuse radiation. Since the diffuse radiation per definition has no incidence angle is used the IAM at  $60^{\circ}$ .

The incidence angle modifier for evacuated tube solar collector is to be treated different, since the evacuated tube collectors are optically non-symmetric.

The longitudinal incidence angle is measured in a plane that is perpendicular to the collector plane and contains the collector azimuth. The corresponding IAM is referred to as the longitudinal IAM, or altitude modifier.

The transversal incidence angle is measured I a plane that is perpendicular to both the collector aperture and the longitudinal plane. The corresponding IAM is referred to as the transversal IAM, or azimuthal modifier.



The Longitudinal incidence angle,  $\theta_l$  is found by

$$\theta_l = abs(atan(\tan \theta_Z * \cos(\omega - \gamma)) - s)$$

Where

 $\theta_z$  is the Solar zenith angle  $\omega$  is the hour angle  $\gamma$  is the orientation of the solar collector s is the inclination of the solar collector.

And transversal incidence angle,  $\theta_t$  is found by

$$\theta_t = abs\left(atan\left(\frac{\sin\theta_Z * \sin(\omega - \gamma)}{\cos\theta}\right)\right)$$

Where

 $\theta$  is the angle of incidence of beam radiation on inclined plane.

When specifying the evacuated tube solar collector, the IAM is specified for both the longitudinal and the transversal incidence angle.

The overall Incidence Angle Modifier for beam radiation,  $K_{\theta}(\theta_l,\theta_t)$  is found by

 $K_{\theta}(\theta_{l},\theta_{t}) = K_{\theta}(\theta_{l}) * K_{\theta}(\theta_{t})$ 

The values of  $K_{\theta}(\theta_l)$  and  $K_{\theta}(\theta_t)$  is found by interpolating between the nearest values in the table of Incidence angle modifier.

The IAM for diffuse radiation is calculated by evaluating the ratio of absorbed diffuse radiation over to incident diffuse radiation over the sky dome for a horizontal collector, assuming isotropic diffuse radiation:

$$K_{\theta diff} = \frac{4}{\pi} \int_{2}^{\pi/2} \int_{2}^{\pi/2} K_{\theta}(\theta, \omega) * \cos \theta * \sin \theta * d\theta * d\omega$$

This integration is performed once at the start of the simulation, with the user supplied IAM data.

Including  $K_{\theta}$  the formula for the heat production from the solar collector becomes:

$$Y = A * \left( \left( I_{beam} * K_{\theta} + (I_{diffuse}) * K_{\theta \text{tiff}} \right) * n_o - a_1 * (t_m - t_a) - a_2 * (t_m - t_a)^2 \right)$$

### 3.6 Photovoltaic

The electricity production from a Photovoltaic module, P<sub>pv</sub>, can be expressed as follows:

$$P_{pv} = P_{Max} * \frac{I_s}{I_{STC}} * \left[1 - \gamma_s * \left(T_{cell} - T_{STC}\right)\right]$$

where

P <sub>max</sub> :	Installed capacity [W]
I <sub>s</sub> :	Solar radiation $[W/m^2]$
I <sub>STC</sub> :	Radiation at standard conditions $(1000 \text{ W/m}^2) [\text{W/m}^2]$
$\gamma_s$ :	Temperature coefficient for module efficiency [-]
T <sub>cell</sub> :	Operation cell temperature [°C]
T <sub>STC</sub> :	The cell temperature at standard conditions (25 °C) [°C]

The operation cell temperature is calculated by the following formula (Antonio Luque and Steven Hegedus (2003)):

$$T_{cell} = T_a + I_s * \left(\frac{NOCT - 20^{\circ}C}{800W/m^2}\right)$$

where:

Tat:Ambient temperatureNOCT:Nominal Operating Cell Temperature

Hereto come losses from the pv-module to the grid,  $\lambda_{misc}$ , such as miscellaneous PV array losses and other power conditioning losses.

The power production at grid becomes:

 $P_{elec} = P_{pv} * (1 - \lambda_{misc})$