



Solar Collectors and Photovoltaic
in energyPRO
with array shading

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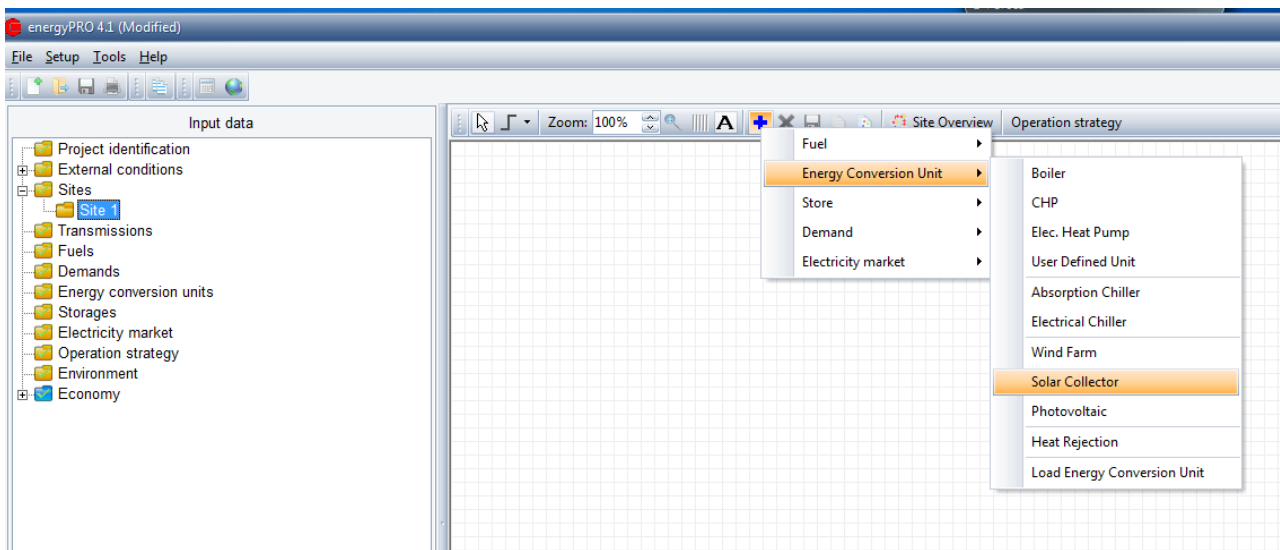
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1. Introduction

With version 4.1.2 of energyPRO is introduced solar collector producing heat and photovoltaic producing electricity 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).

2. User interface

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



2.1 Solar collector

The window for the solar collector has the following appearance:

The screenshot shows the 'Solar Collector' configuration window. It is divided into several sections:

- Name:** Solar Collector
- Size and Position:**
 - Total area of collectors: 1000 m²
 - Latitude (UTM): 51,0 degree
 - Inclination of solar collector: 35 degree
 - Orientation of solar collector (Deviation from South): 0 degree
- Non availability periods:**
- Select Input Time Series:**
 - Ambient temperatures: Hourly outdoor temperature
 - Radiation on horizontal plane:
 - Aggregated Radiation
 - Direct and Diffuse Radiation
 - Aggregated radiation: Aggregated solar radiation
- Collector specification:**
 - Start efficiency (η_0): 0,815
 - Loss coefficient (a_1): 2,430 W/(m² °C)
 - Loss coefficient (a_2): 0,012 W/(m² °C)²
 - Incidence angle modifier:
 - Coefficient: 4,000
 - K^θ at 50 degree: 0,953
- Collector field specifications:**
 - Temperatures on: collector side of heat exchanger
 - Temperature drop over heat exchanger: 0,00 °C
 - From collector: <Constant> 80,00 °C
 - To collector: <Constant> 40,00 °C
 - Losses in pipes in collector field in percentage of production: 1%
- Include effects of array shading:**

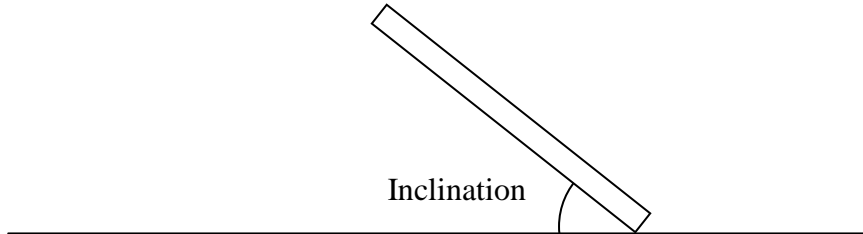
At the bottom, a status bar reads: "The collector specifications are valid for an Arcon HT solar collector." The window has 'OK' and 'Cancel' buttons at the bottom right.

We have three 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 four 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 latitude has to be in accordance with the latitude of the time series with the radiation.

The inclination of the solar collector is measured from horizontal:



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 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.

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.

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 energy-PRO 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 production unit photovoltaic:

Solar photovoltaic

Name: Solar photovoltaic

Size and Position

Installed capacity: 500,0 kW

Latitude (UTM): 51,0 degree

Inclination of photovoltaic: 35 degree

Orientation of photovoltaic (Deviation from South): 0 degree

Non availability periods

Select Input Time Series

Ambient temperatures: Hourly outdoor temperature

Radiation on horizontal plane

Aggregated Radiation

Direct and Diffuse Radiation

Aggregated radiation: Aggregated solar radiation

Include effects of array shading

PV module specification

Maximum power: 100 W

Temperature coefficient of power: 0,400 %/°C

NOCT: 45 °C

Miscellaneous

Aggregated Losses from module to grid: 10,0 %

Number of PV modules: 5000

Comments:

OK Cancel

We have 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.

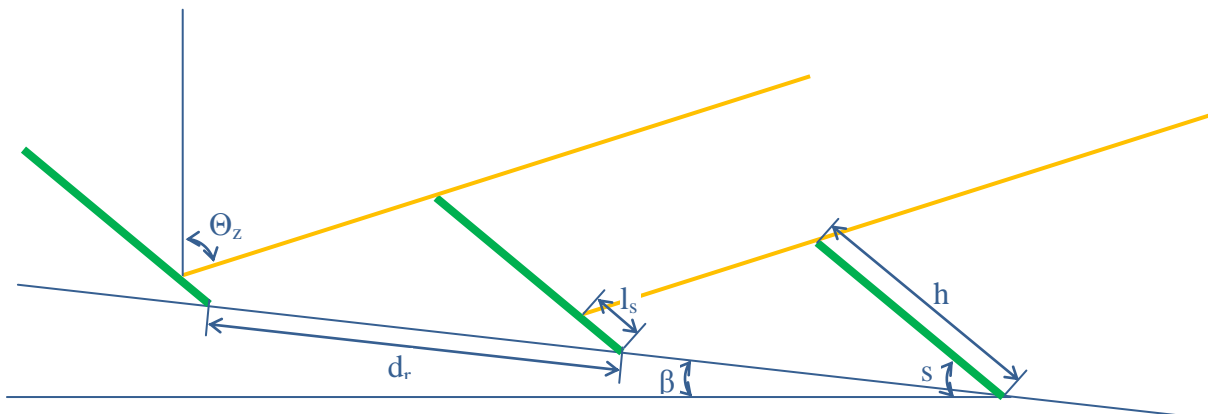
2.3 Array shading

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.

| | | | | | |
|--|---------------------------------------|--|---------------------------------------|---------------|-------------------------------------|
| <input checked="" type="checkbox"/> Include effects of array shading | | | | | |
| Number of rows | <input type="text" value="10"/> | Distance between rows | <input type="text" value="4,50"/> m | Height, units | <input type="text" value="2,27"/> m |
| Inclination, ground | <input type="text" value="0"/> degree | Orientation of ground (Deviation from south) | <input type="text" value="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.

Any inclination and orientation of the ground can also be included.



3. Method of calculation

3.1 Definitions

| | | |
|----------------------------|---------------------------------------|--|
| α | [°] | Solar altitude angle ($90^\circ - \theta_z$) |
| ϕ | [°] | Latitude |
| δ | [°] | Solar declination angel |
| γ | [°] | Orientation of inclined plane, south = 0° , west = 90° |
| γ_t | [] | Temperature coefficient for photovoltaic module efficiency |
| θ | [°] | Angel of incidence of beam radiation on inclined plane |
| ω | [°] | Hour angel |
| ρ | [] | Reflection factor |
| θ_z | [°] | Solar zenith angle (angel of incidence of beam radiation on horizontal) |
| λ_{misc} | [] | Losses from the photovoltaic-module to the grid |
| a | [] | Incidence angle modifier coefficient |
| A | [m ²] | Total solar collector area |
| I | [W/m ²] | Total radiation on a horizontal plane |
| I _b | [W/m ²] | Beam radiation on a horizontal plane |
| I _d | [W/m ²] | Diffuse radiation on a horizontal plane |
| I _{diff} | [W/m ²] | Diffuse radiation on an inclined plane |
| I _{dir} | [W/m ²] | Beam radiation on an inclined plane |
| I _o | [W/m ²] | Extraterrestrial radiation on a horizontal plane |
| I _{ref} | [W/m ²] | Ground reflected radiation on an inclined plane |
| I _s | [W/m ²] | Total radiation on an inclined plane |
| I _{sc} | [W/m ²] | Solar constant, 1367 W/m ² |
| I _{STC} | [W/m ²] | Radiation at standard conditions (1000 W/m ²) (photovoltaic) |
| K _θ | [] | Incidence angle modifier |
| k ₀ | [W/(m ² °C) ²] | First-order coefficient in collector efficiency equation |
| k ₁ | [W/(m ² °C)] | Second-order coefficient in collector efficiency equation |
| K _T | [] | Ratio of total radiation on a horizontal plane to extraterrestrial radiation |
| n | [] | Day of year |
| n ₀ | [] | Intercept (maximum) of the collector efficiency |
| NOCT | [°C] | Nominal Operating Cell Temperature (photovoltaic) |
| P _{p_v} | [W] | Electricity production from a Photovoltaic module |
| P _{max} | [W] | Installed capacity, photovoltaic |
| P _{elec} | [W] | Electricity production to the grid from the photovoltaic plant |
| R _b | [] | Ratio of beam radiation on an inclined plane to beam on horizontal |
| R _d | [] | Ratio of diffuse radiation on an inclined plane to diffuse on horizontal |
| R _r | [] | Ratio of reflected radiation on an inclined plane to total radiation on horizontal |
| s | [°] | Inclination of surface |
| t _a | [°C] | Ambient temperature |
| t _m | [°C] | Solar collectors average temperature |
| T _{cell} | [°C] | Photovoltaic operation cell temperature |
| T _{STC} | [°C] | The cell temperature at standard conditions (25 °C) (photovoltaic) |

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

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

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

I_o is defined as:

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

where I_{sc} is the solar constant, 1367 w/m^2
 θ_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 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_b .

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

where θ_z Angel of incidence of beam radiation on horizontal.

Angel of incidence of beam radiation on horizontal is specified by the formula:

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

where δ is the solar declination angel
 ϕ is the latitude
 ω is the hour angel

The solar declination angel is approximately specified by:

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

where n is the day of the year.

The hour angel is identified by ("European simplified methods for active solar system design", Bernard Bourges, July 1990):

$$\omega = 15 * (h - 12) \text{ (Expressed in degrees)}$$

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

$$\begin{aligned} \cos \theta = & \sin \delta * \sin \phi * \cos s - \sin \delta * \cos \phi * \sin s * \cos \gamma \\ & + \cos \delta * \cos \phi * \cos s * \cos \omega \\ & + \cos \delta * \sin \phi * \sin s * \cos \gamma * \cos \omega \\ & + \cos \delta * \sin s * \sin \gamma * \sin \omega \end{aligned}$$

where s is the inclination of the plane
 γ is the plane's orientation.

The beam radiation on an inclined plane:

$$I_{dir} = I_b * R_b$$

3.3.2 Diffuse radiation

The ratio between the diffuse radiation on an inclined plane and horizontal is given by

$$R_d = 0,5 * (1 + \cos s)$$

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 ρ 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

$$I_{ref} = I * R_r$$

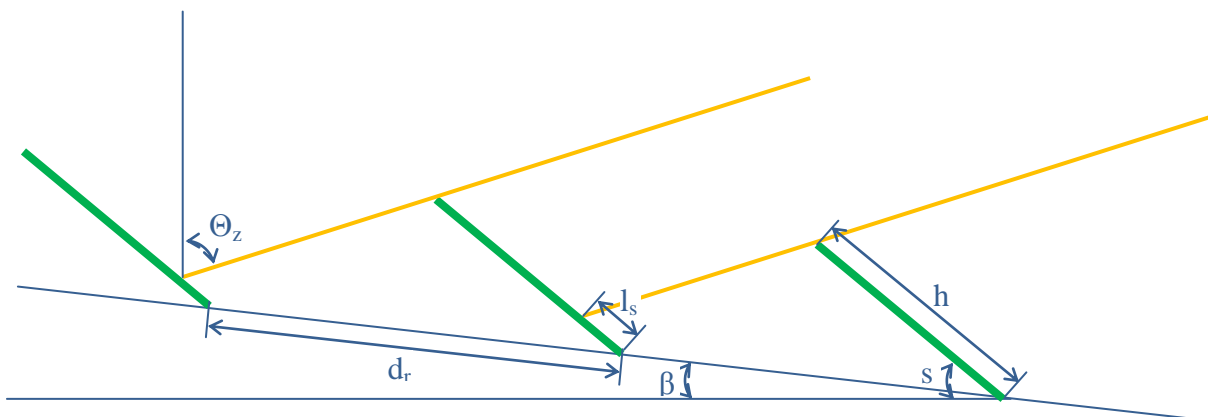
3.3.4 Total radiation

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:

- β_{gr} [°] The inclination of the ground
- γ_{gr} [°] The orientation of the ground related to south
- s [°] The inclination of the surfaces
- γ_{surf} [°] The orientation of the surfaces related to south
- h [m] The height of surfaces
- d_r [m] The distance between the rows related to the ground
- ϕ [°] The latitude of location
- N_{rows} [] The number of rows
- ω [°] The solar hour angle
- Θ_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, ω .

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

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

The height of the surface in the hour angle, h_ω is found by the following cosine relation:

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

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:

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

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 ground's inclination in the orientation of the surfaces:

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

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_{frac} is calculated as follows

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

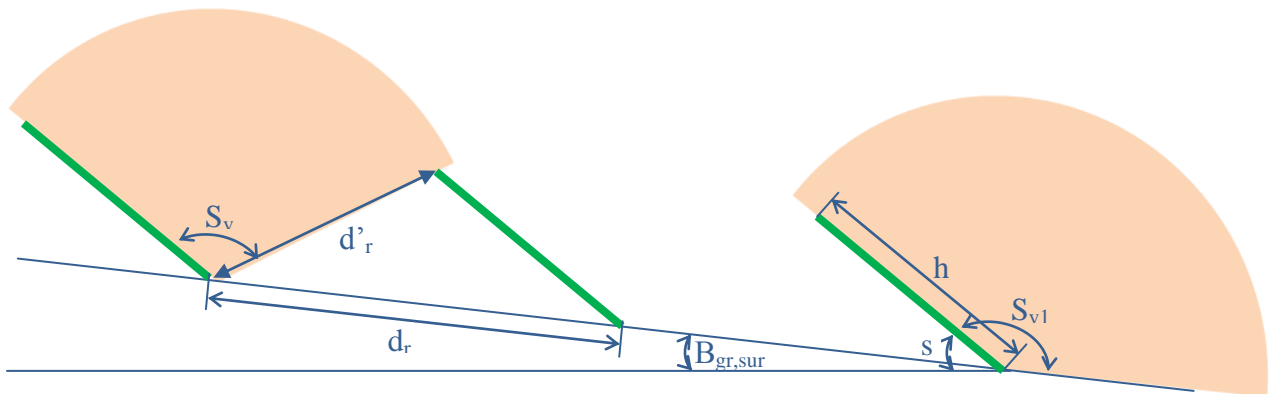
Where N_{rows} is the number of rows.

With correction for array shading the beam radiation becomes

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

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 preceding 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_{d1} is given by

$$R_{d1} = 0,5 * (1 + \cos(s - \beta_{gr,surf}))$$

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

$$R_d = 0,5 * (1 + \cos(180 - S_v))$$

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'_r is the distance between the bottom of the row and the top of the preceding row.

d'_r 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

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

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 $r_{p-1,b}$ becomes

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

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

The reflected beam radiation, $R_{r,b}$ 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

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

The diffuse reflected radiation, $R_{rn,d}$ 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):

$$Y = A * \left(I_s * n_o - k_1 * (t_m - t_a) - k_2 * (t_m - t_a)^2 \right)$$

where

- Y: heat production, [W].
- A: Solar collector area [m²]
- I_s: Solar radiation on solar collector, [W/m²]
- t_m: 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_a: 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:

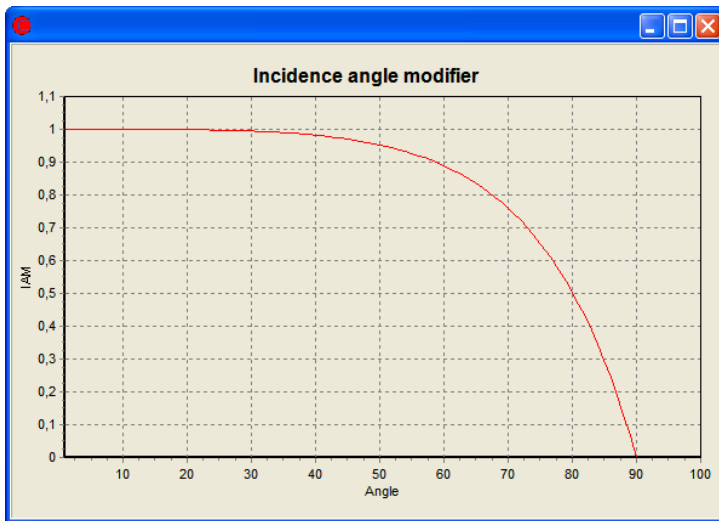
- n_o: Intercept (maximum) of the collector efficiency, [-]
- k₁: The first-order coefficient in collector efficiency equation, [W/(m² °C)]
- k₂: The second-order coefficient in collector efficiency equation, [W/(m² °C)²]

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_o , k_1 and k_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_θ . 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 looks as below:



It can also be defined as follow:

$$K_\theta = 1 - \tan^a(\theta/2)$$

where θ is the incidence angel on the collector.
 a is the measured coefficient.

Including K_θ the formula for the heat production from the solar collector becomes:

$$Y = A * \left((I_{beam} * K_\theta + (I_{diffuse}) * K_{60^\circ}) * n_o - k_1 * (t_m - t_a) - k_2 * (t_m - t_a)^2 \right)$$

The radiation is split into beam radiation and diffuse radiation. Since the diffuse radiation per definition has no incidence angel is used the IAM at 60°.

3.6 Photovoltaic

The electricity production from a Photovoltaic module, P_{pv} , can be expressed as follows:

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

where

| | |
|--------------|---|
| P_{max} : | Installed capacity [W] |
| I_s : | Solar radiation [W/m^2] |
| I_{STC} : | Radiation at standard conditions ($1000 W/m^2$) [W/m^2] |
| γ_s : | Temperature coefficient for module efficiency [-] |
| T_{cell} : | Operation cell temperature [$^{\circ}C$] |
| T_{STC} : | The cell temperature at standard conditions ($25^{\circ}C$) [$^{\circ}C$] |

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:

| | |
|------------|------------------------------------|
| T_{at} : | Ambient temperature |
| NOCT: | Nominal Operating Cell Temperature |

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

The power production at grid becomes:

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