HOW TO GUIDE

Solar collectors and photovoltaics in energyPRO

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About energyPRO

energyPRO is a Windows-based modeling software package for combined techno-economic analysis and optimisation of complex energy projects with a combined supply of electricity and thermal energy from multiple different energy producing units.

The unique programming in energyPRO optimises the operations of the plant including energy storage (heat, fuel, cold and electrical storages) against technical and financial parameters to provide a detailed specification for the provision of the defined energy demands, including heating, cooling and electricity use.

energyPRO also provides the user with a detailed financial plan in a standard format approved by international banks and funding institutions. The software enables the user to calculate and produce a report of the emissions by the proposed project.

energyPRO is very user-friendly and is the most advanced and flexible software package for making a combined technical and economic analysis of multi-dimensional energy projects.

For further information concerning the applications of energyPRO please visit www.emd.dk.

Terms of application

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Contents

In this How To Guide you will learn how to set up solar collectors and photovoltaics in energyPRO. For both technologies energyPRO offers a built-in unit in which all relevant formulas are incorporated, making the modelling simpler. Based on time series with solar radiation and ambient temperatures, information about location, orientation and performance (found in datasheets from the manufacturer), the operation of the unit is calculated.

In the end of the guide, the formulas and applied theories behind these built-in units are described.

Click the bullets below to jump to the relevant chapter.

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Flat plate solar collectors and evacuated tube solar collector

Add a flat plate solar collector or an evacuated tube solar collector by clicking the blue plus icon in the toolbar as shown in Figure 1. Select "Energy Conversion Unit" in the menu box and then select either the flat plate or evacuated tube solar collector.

You can also access this menu box by right clicking a random place in the editing window (canvas).

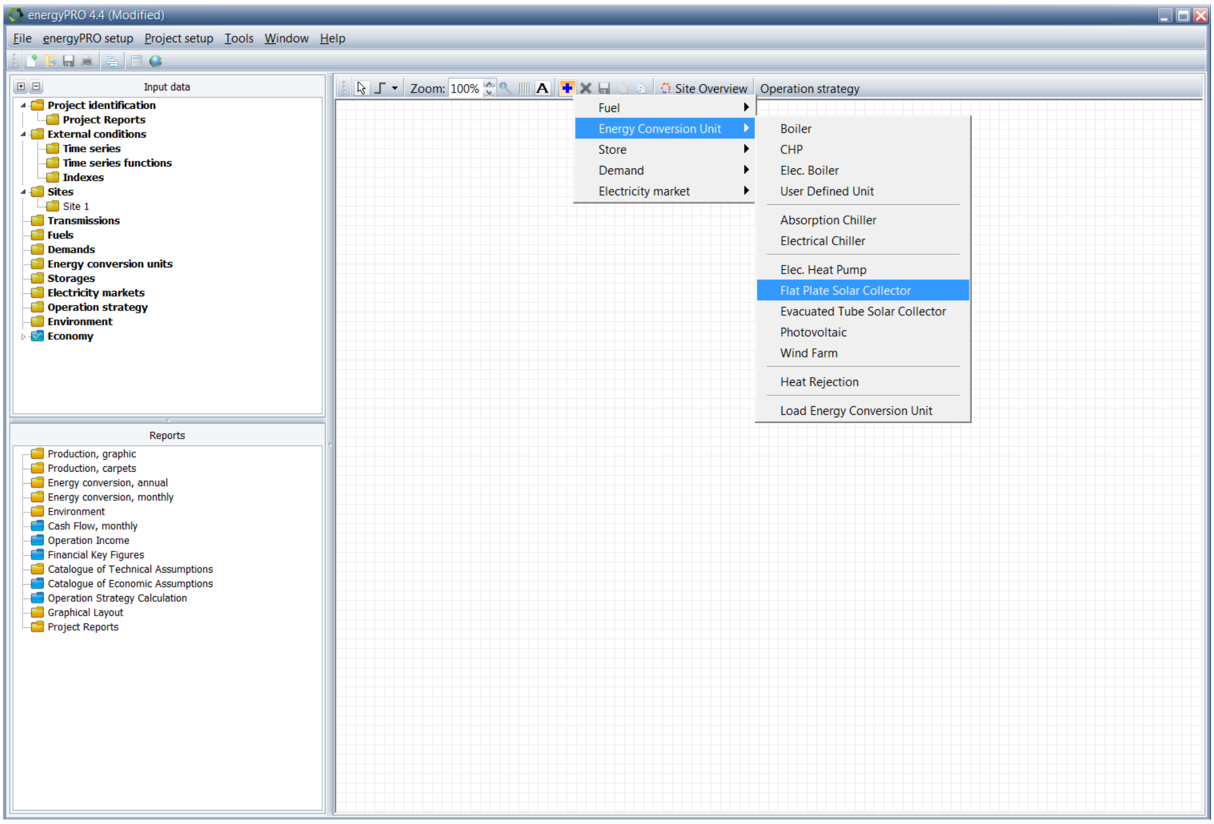

Figure 1. Add a flat plate or evacuated tube solar collector by clicking on the blue plus in the toolbar

Once the solar collector has been added, a window with its technical specifications will open automatically. The window will look similar to the one in Figure 2. The only difference in the settings of the two types of solar collectors are the "Incidence angle modifier". Otherwise the settings are the same.

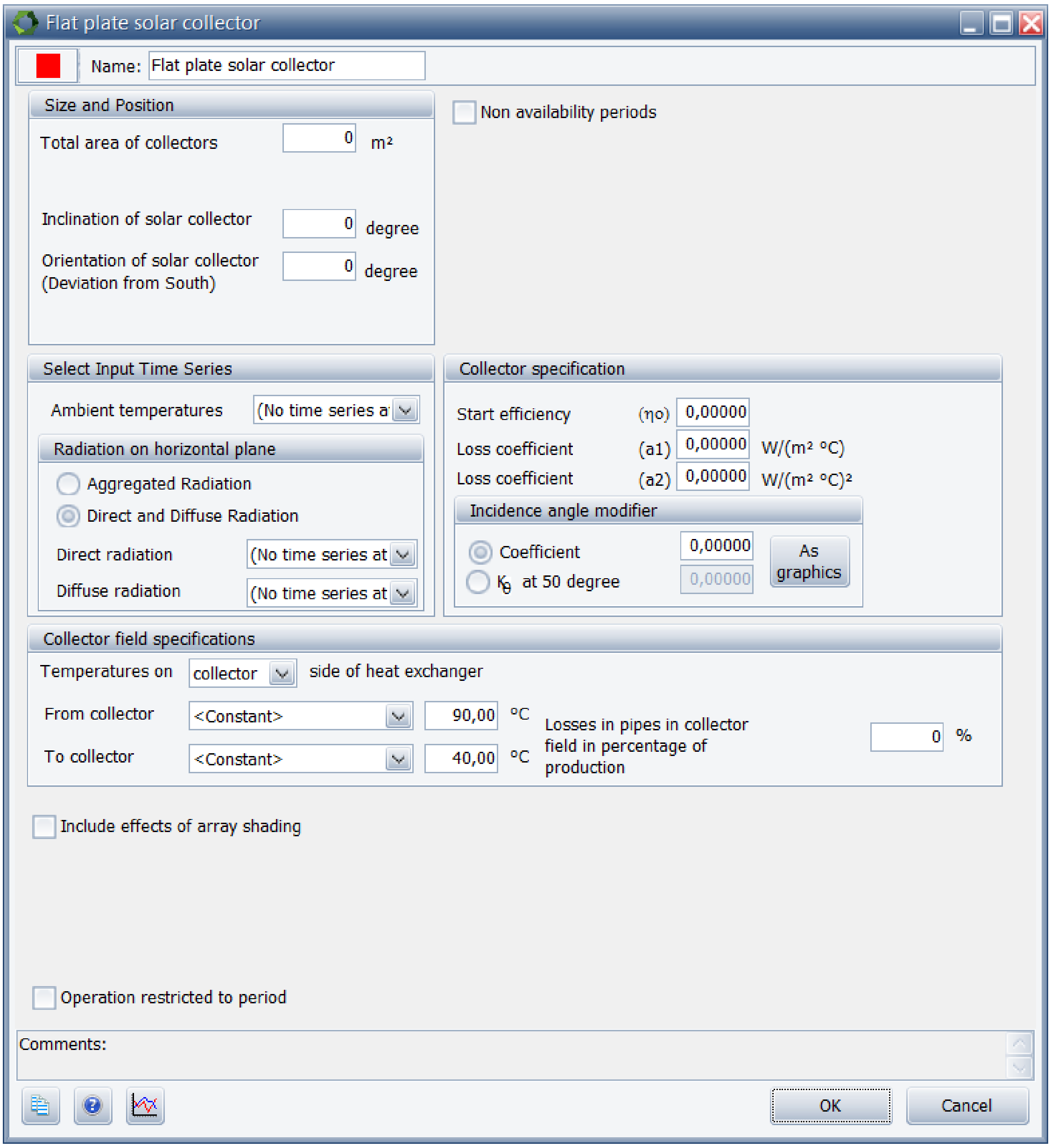

Figure 2. The specifications of the flat plate solar collector unit

The specifications are divided into four main sections: "Size and Position", Select Input Time Series", "Collector field specifications" and "Collector specifications".

In addition, you have the option of enabling effects of array shading. Read more in the section about array shading in page 12.

Size and Position

Size and position of the collectors includes three input fields. The first field is the total area of the collectors, which must be stated 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 second field is the inclination of the solar collector, which is the angle from horizontal as shown on Figure 3.

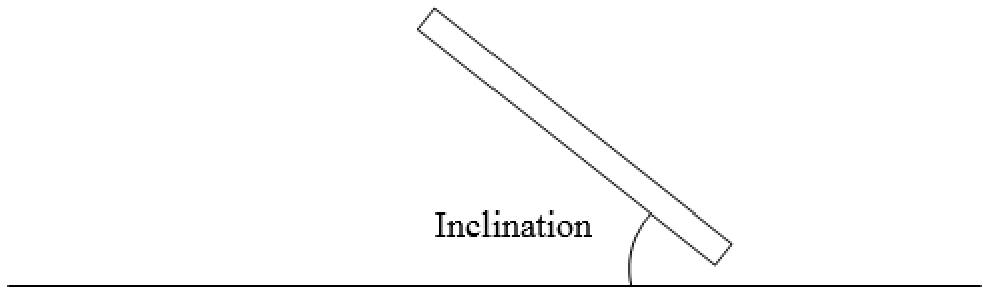

Figure 3. Inclination of the solar collector

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

Input Time Series

The input time series includes ambient temperatures and solar radiation. Select the relevant time series from the drop down menu. For more accurate results, use time series with hourly values.

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

The time series must be included as time series under External conditions.

Collector field specifications

In the collector field specifications, the temperatures of the fluid are set. The temperature from and to the collectors can either be in form of fixed values or as 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. If the user selects the demand side of the heat exchanger, the temperature drop across the heat exchanger is t_{hx}. 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 have an influence. Losses in pipes in collector field in percentage of production can be specified.

Collector specification

Information regarding the collector specifications has to be delivered by the manufacture of the collectors. For more information about the start efficiency and loss coefficients, please refer to page 23 in Calculation methodology.

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

For the evacuated tube solar collector, the input to the incidence angle modifier looks like on Figure 4.

Incidence angle modifier

Degree	0,00	10,00	20,00	30,00	40,00	50,00	60,00	70,00	90,00
Kθ(θT)	1,00	1,01	1,01	1,02	1,03	0,99	1,05	1,10	0,00
Kθ(θL)	1,00	1,00	1,00	0,99	0,97	0,95	0,89	0,65	0,00

Add Remove As graphics

Figure 4. Incidence angle modifier for the evacuated tube solar collector

Evacuated tube collectors are optically non-symmetric. The incidence angle modifier is divided into a longitude and transversal IAM. Converted to graphic, the above values look as shown on Figure 5.

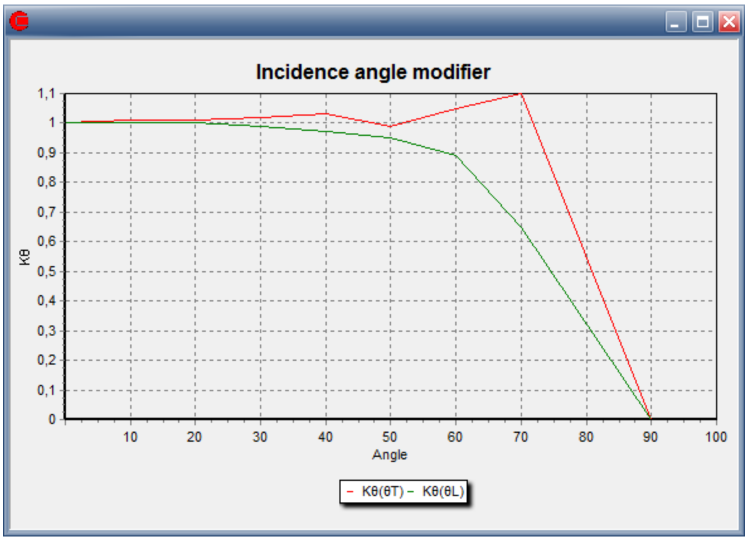

Figure 5. Incidence angle modifier as graphic

Photovoltaics

As with the solar collector, add a PV-unit by clicking the blue plus icon as shown in Figure 1 and select the Photovoltaic in the Energy Conversion Unit menu.

Once added, double-click the unit to open its specification window like the one shown in Figure 6.

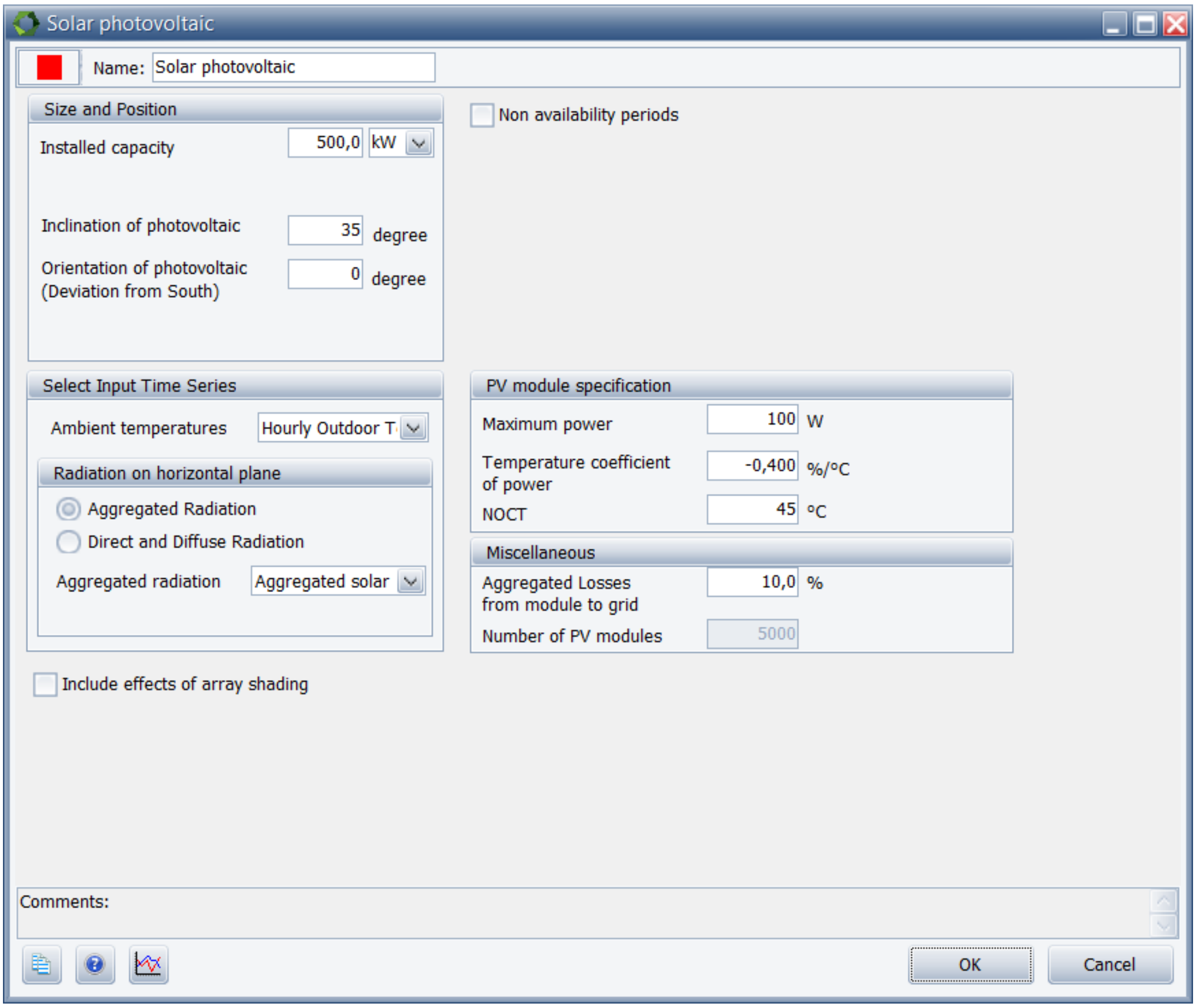

Figure 6. Window to set up the photovoltaic unit

There are three groups of information: “Size and Position”, “Select Input Time Series” and “PV module specification”.

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

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 about these values, please refer to page 26 in Calculation methodology.

In addition, you have the option of enabling effects of array shading. Read more in the section about array shading in page 12.

Location of 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.

This is set in the time series with the solar radiation as seen below. Double-click the relevant time series to open it.

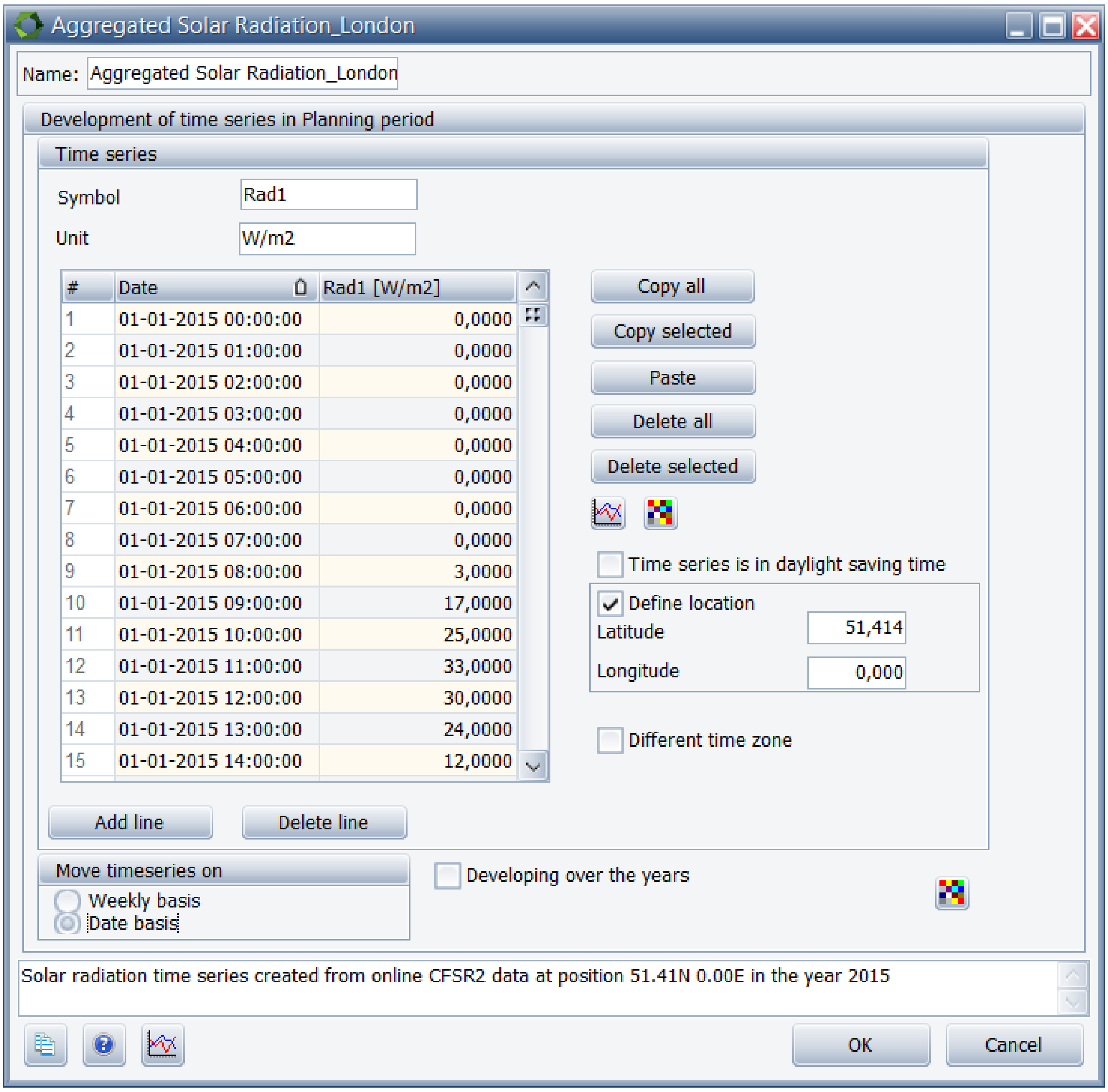

Figure 7. Time series for solar radiation

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, whereas 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.

Array shading

The calculated radiation on an inclined surface is valid for single rows only. Often, large scale solar collector or photo voltaic systems will be mounted on the ground in rows and the radiation will be reduced due to shading on the subsequent rows. Enabling 'Include effects of array shading' will take that into account and can be found in the set up window as shown on Figure 8.

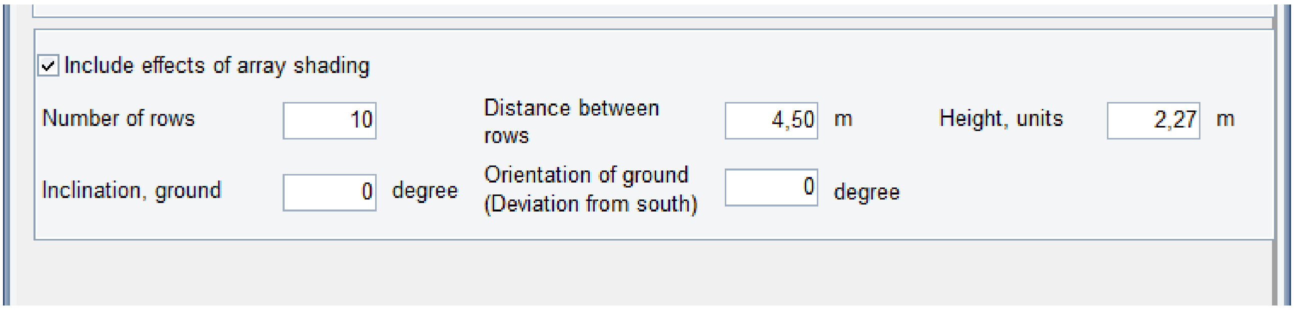

Figure 8. Inclusion of array shading

The number of rows is used for calculating the ratio between the first row without shading 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. A visualization of inclination and orientation can be seen on Figure 9.

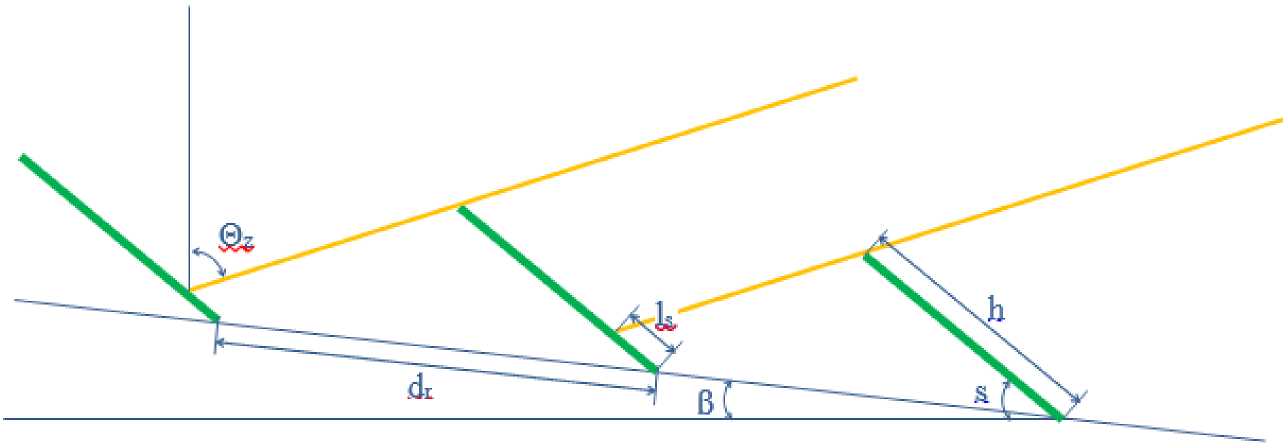

Figure 9. Inclination and orientation of the ground

As illustrated in the figure, a higher inclination of the ground will result in a reduced shading effect.

Calculation methodology

In the following are the definitions and mathematical expressions used to calculate on solar collectors and photovoltaics presented.

Nomenclature

α	[°]	Solar altitude angle (90° - θ_z)
ϕ	[°]	Latitude
δ	[°]	Solar declination angle
γ	[°]	Orientation of inclined plane, south = 0°, west = 90°
γ_t	[]	Temperature coefficient for photovoltaic module efficiency
θ	[°]	Angle of incidence of beam radiation on inclined plane
θ_l	[°]	Longitudinal angle of incidence of beam radiation on inclined plane
θ_t	[°]	Transversal angle of incidence of beam radiation on inclined plane
ω	[°]	Hour angle
ρ	[]	Reflection factor
θ_z	[°]	Solar zenith angle
λ_{misc}	[]	Losses from the photovoltaic-module to the grid
a	[]	Incidence angle modifier coefficient
A	[m^2]	Total solar collector area
A_I	[]	Anisotropy index
f	[]	Modulating factor
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/m2]	Total radiation on an inclined plane
I_{sc}	[W/m2]	Solar constant, 1367 W/m^2
I_{bn}	[W/m2]	Beam radiation at normal incidence
I_{on}	[W/m2]	Extraterrestrial radiation at normal incidence
I_{STC}	[W/m^2]	Radiation at standard conditions (1000 W/m^2) (photovoltaic)
K_θ	[]	Incidence angle modifier
$K_\theta(\theta_l)$	[]	Longitudinal incidence angle modifier
$K_\theta(\theta_t)$	[]	Transversal incidence angle modifier
a_1	[$W/(m^2\ °C)$]	First-order coefficient in collector efficiency equation
a_2	[$W/(m^2\ °C^2)$]	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_{pv}	[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 level
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]	Cell temperature at standard conditions (25 °C) (photovoltaic)
T_{TST}	h]	True Solar Time
T_z	[h]	Zone time or local time
T_j	[h]	Equation of time
K	[°]	Local Constant
Cor_{DST}	[h]	Correction for daylight saving time

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: $0 \leq K_T \leq 0{,}3$	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 the next section.

The beam radiation is

$$I_b = I - I_d$$

Radiation on solar collector or photovoltaic

This section describes the calculation of radiation on an unshaded surface. The effects of array shading are described in page 18.

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

Beam radiation

The relation between the beam radiation on an inclined plane and the beam radiation on horizontal is given by the factor R_b..

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

where θ is the 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 δ is the solar declination angle.

ϕ is the latitude

ω 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, ω, is defined by:

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

where T_{TST} is True Solar Time. True Solar Time is defined in page 16.

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

γ is the plane's orientation.

The beam radiation on an inclined plane:

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

True Solar Time

The conversion 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

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

where B is in degrees and found by

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

where n is number of days in a year.

T_j varies from approximately -15 minutes to approximately + 17 minutes as can be seen on Figure 10.

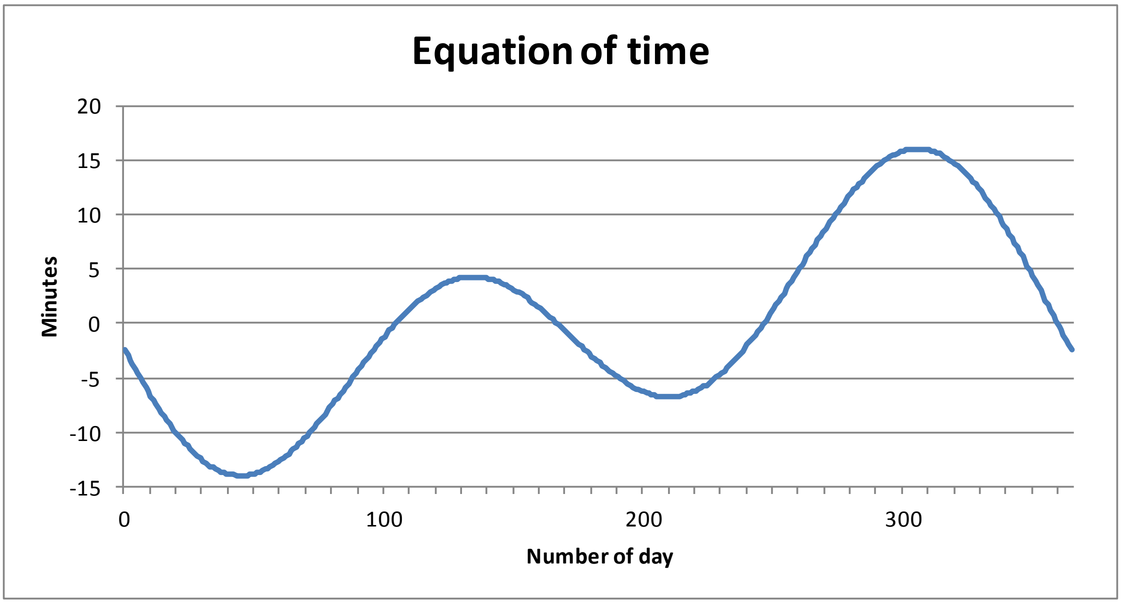

Figure 10. The equation of time

The Local Constant, K, is found by

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

Where l_m is 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 rises or sets 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.

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):

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

where A_I is Anisotropy index

f is modulating factor

A_I is defined as follows:

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

where I_{bn} is the beam radiation at normal incidence

I_{on} is the 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 θ = 0.

Hereby the diffuse radiation on the inclined plane:

$$I_{diff} = I_d * R_d$$

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

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

Total radiation

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

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

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.

An example here of can be seen on Figure 11.

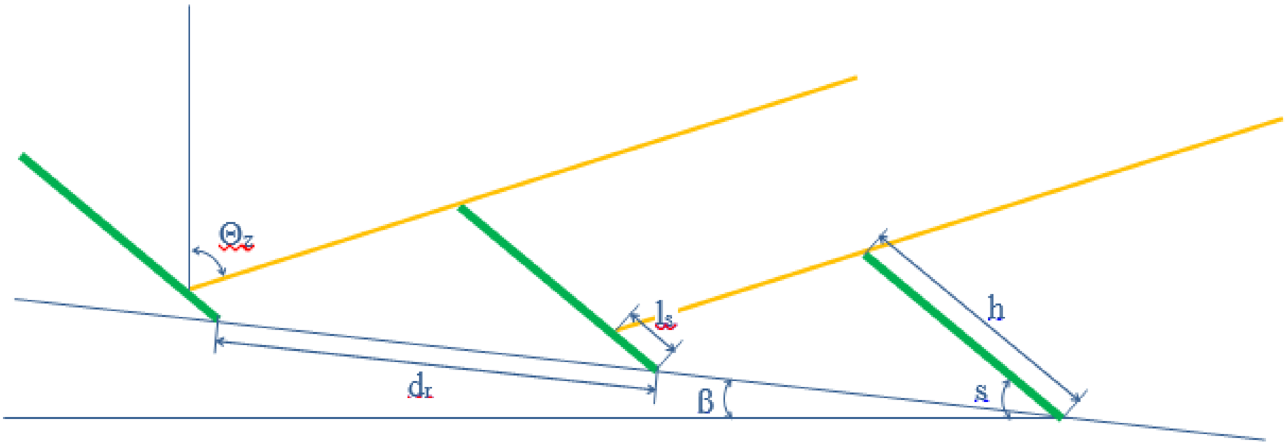

Figure 11. Multiple units resulting in array shading

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

βgr	[°]	The inclination of the ground
γgr	[°]	The orientation of the ground related to south
s	[°]	The inclination of the surfaces
γsurf	[°]	The orientation of the surfaces related to south
h	[m]	The height of surfaces
dr	[m]	The distance between the rows related to the ground
φ	[°]	The latitude of location
Nrows	[]	The number of rows
ω	[°]	The solar hour angle
Θz	[°]	The solar zenith angle

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:

$$l_s = h - \frac{d_r}{\sin\left(180 - s - (90 - \theta_z)\right)} * \sin(90 - \theta_z)$$

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.

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

Diffuse radiation

The shadow impact on the diffuse radiation is visualized below.

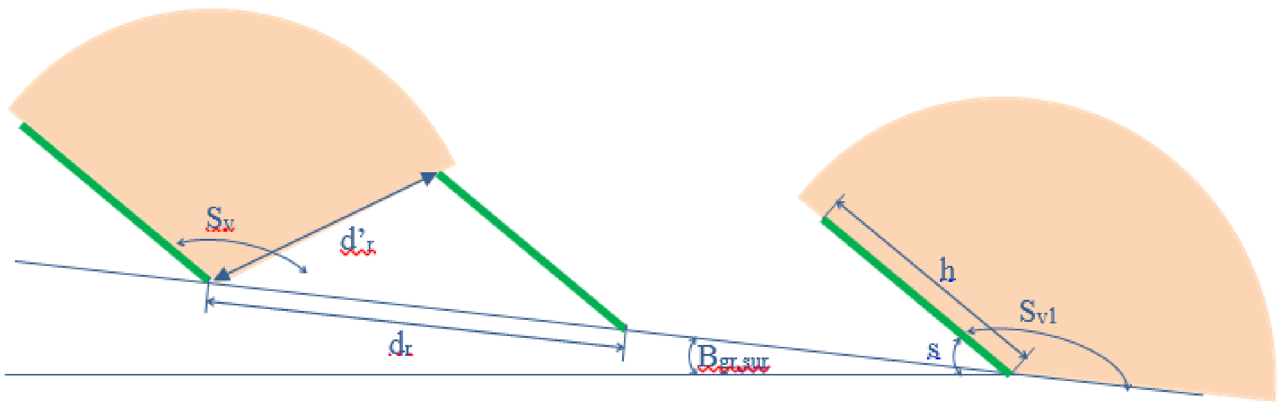

Figure 12. Shadow impact on the diffuse radiation

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_{d1} is given by

$$R_{d1} = 0{,}5 * (1 - A_I) * \left(1 + \cos(s - \beta_{gr,surf})\right) * \left(1 + (f) * \sin^3\left({}^{s}/_{2}\right)\right) + A_I * R_b$$

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

$$R_d = 0{,}5 * (1 - A_I) * (1 + \cos(180 - s_v)) * \left(1 + (f) * \sin^3\left({}^{s}/_{2}\right)\right) + A_I * R_b * (1 - \mathrm{Sh_{frac}})$$

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'_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

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

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

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

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

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

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:

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

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

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

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

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

Solar Collector

The formula for a solar collector is as follows (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^2]

I_s: Solar radiation on solar collector, [W/m^2]

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, [-]

a_1: The first-order coefficient in collector efficiency equation, [$W/(m^2\ °C)$]

a_2: The second-order coefficient in collector efficiency equation, [$W/(m^2\ °C^2)$]

These 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, 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_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 for a flat plate solar collector looks as the one shown on Figure 13.

Figure 13. Incidence angle modifier for a flat plate solar collector

It can also be defined as

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

where θ is the incidence angle on the collector.

a is the measured coefficient.

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

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

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

The incidence angle modifier for evacuated tube solar collector is to be treated differently 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 in 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.

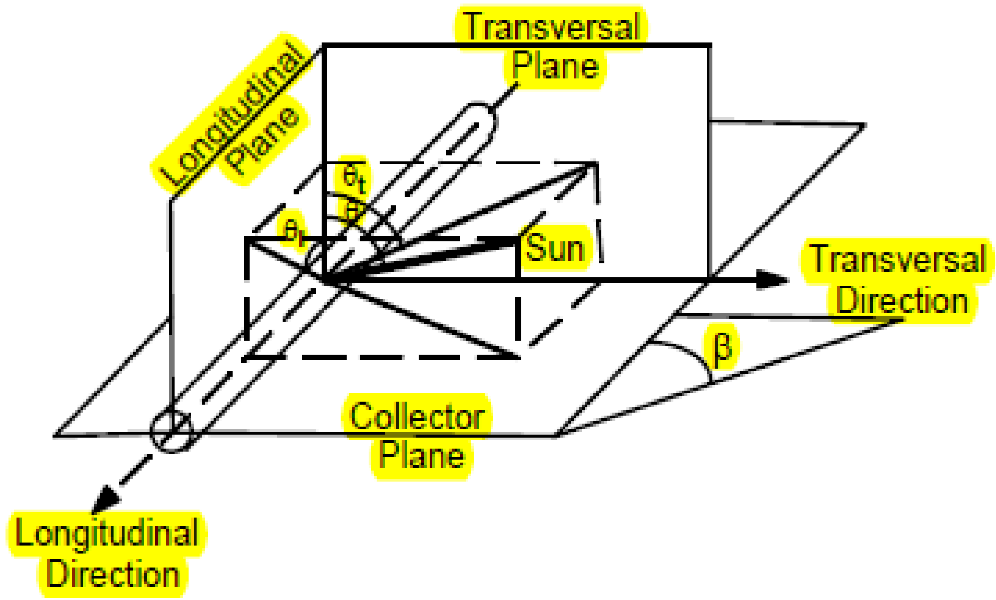

Figure 14. The transversal incidence angle

The Longitudinal incidence angle, θ_l is found by

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

where

θ_z is the Solar zenith angle

ω is the hour angle

γ is the orientation of the solar collector

s is the inclination of the solar collector.

And the transversal incidence angle, θ_t is found by

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

where

θ 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_θ the formula for the heat production from the solar collector becomes

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

Photovoltaic

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

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

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 [°C]

T_{STC}: 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)):

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

where

T_{at}: Ambient temperature

NOCT: Nominal Operating Cell Temperature

Hereto comes 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:

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

Please notice, that you can find more information on how to use energyPRO in the How to Guides, User's Guide and tutorials on EMD's website:

http://www.emd.dk/energypro/

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