

# **Description of the Energy Output Calculator, a program for calculation of annual solar collector energy output**

Energy Output Calculator v3.05 RELEASED – general version – unlocked – Sept 2011.xls

## **Introduction**

This document summarises how to use the Energy Output Calculator to evaluate annual solar collector output. The document also describes the equations used to calculate collector power output each time step. The tool is primarily developed to give the end-user a possibility to compare different types of solar collectors. The program shall therefore not be used as a calculation tool for design of solar energy installations. No system is simulated. The calculations assume that there is a load all the time for the energy collected and that the collector is operating at a constant average temperature. The tool is applicable to all kinds of liquid heating collectors, including tracking concentrating collectors, collectors with multi axial incidence angle modifiers and unglazed collectors.

## **System requirements**

The tool is constructed using Microsoft Office Excel 2007 SP2 and Visual Basic 6.3. This version should be used for the evaluations. The program has not been tested under other versions of Excel and Visual Basic, but it may be possible to run the program with later versions.

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## Description of the program

### Information flow

The user of this code starts by pressing the button “Start evaluation” Figure 1. In the user interface that then appears, the user is asked to input data, see “User input” below. When the data has been typed, the Visual Basic code calculates the monthly amount of heat that could be extracted from the solar collector. The results are presented as a table and as a graph. The calculation is based on hourly values and hourly output values are also produced, however, these are not shown to the user as default but are presented in a hidden sheet.

### User input

When pressing the “Start evaluation” button, the user is prompted to input information on the location of the collector installation and on the collector mean operating temperatures (which are assumed to be constant over the year). This version is limited to Athens, Davos, Stockholm and Wurzburg and to temperatures from 0°C to 100°C (Figure 2). Location weather data is then taken from a hidden sheet.

Next is the input of collector data. The former are to be chosen according to the test method that has been applied to derive the model parameters (Figure 3 and Figure 4 for Quasi Dynamic or Steady State test data respectively).

After this the input on Incidence Angle Modifier (IAM) type and parameters are supplied (Figure 5).

Finally the type of tracking and tilt angle is chosen (Figure 6) and the “Run” button is pressed to perform the calculations. The output calculation can also be executed or the program can be terminated from either of the three previous tabs.

See also Appendix C “Short explanation of input parameters and description of output data”.

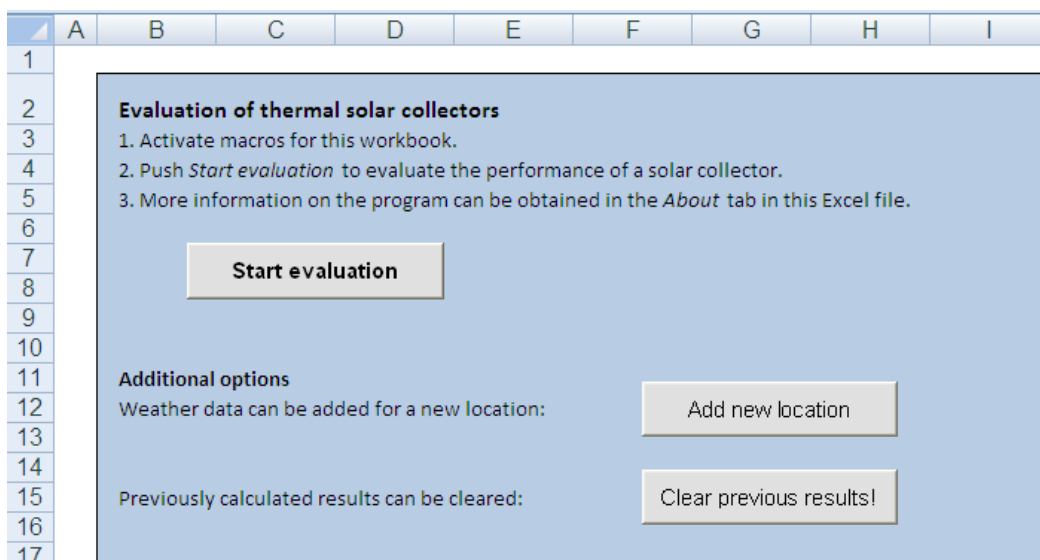


Figure 1. Main screen.

**Evaluation of annual energy output**

**Energy Output Calculator**  
Version 3.05 (September 2011)

Label, location & collector data | Evaluation method & parameters | IAM type | Type of tracking

Identification label for the solar collector:

Location:

Collector mean temperature:  
(0–100°C are valid)  °C  °C  °C

Aperture area  [m<sup>2</sup>]

Figure 2. Location input.

**Evaluation of annual energy output**

**Energy Output Calculator**  
Version 3.05 (September 2011)

Label, location & collector data | Evaluation method & parameters | IAM type | Type of tracking

Choose evaluation method:  
 Steady State (Acc. to EN 12975-2, Chapter 6.1)  
 Quasi Dynamic Testing (Acc. to EN 12975-2, Chapter 6.3)

$F'(t, \alpha)_{en}$   [-] (based on aperture)  Options for unglazed collectors

$K_{B,d}$   [-] Diffuse angle modifier.  $c_4$   [-]

$c_1$   [W/m<sup>2</sup>K]  $c_6$   [s/m]

$c_2$   [W/m<sup>2</sup>K<sup>2</sup>]

$c_3$   [J/m<sup>2</sup>K]

$a_1 = c_1 + 3 \cdot c_3$   [W/m<sup>2</sup>K] (based on aperture; including wind 3 m/s)

$a_2 = c_2$   [W/m<sup>2</sup>K<sup>2</sup>] (based on aperture)

Figure 3. Input of collector constants based on Dynamic testing.

**Evaluation of annual energy output**

**Energy Output Calculator**  
Version 3.05 (September 2011)

Label, location & collector data | Evaluation method & parameters | IAM type | Type of tracking

Choose evaluation method:  
 Steady State (Acc. to EN 12975-2, Chapter 6.1)  
 Quasi Dynamic Testing (Acc. to EN 12975-2, Chapter 6.3)

$\eta(0)$   [-] (based on aperture)

$a_1$   [W/m<sup>2</sup>K] (based on aperture)

$a_2$   [W/m<sup>2</sup>K<sup>2</sup>] (based on aperture)

Figure 4. Input of collector constants based on Steady State testing.

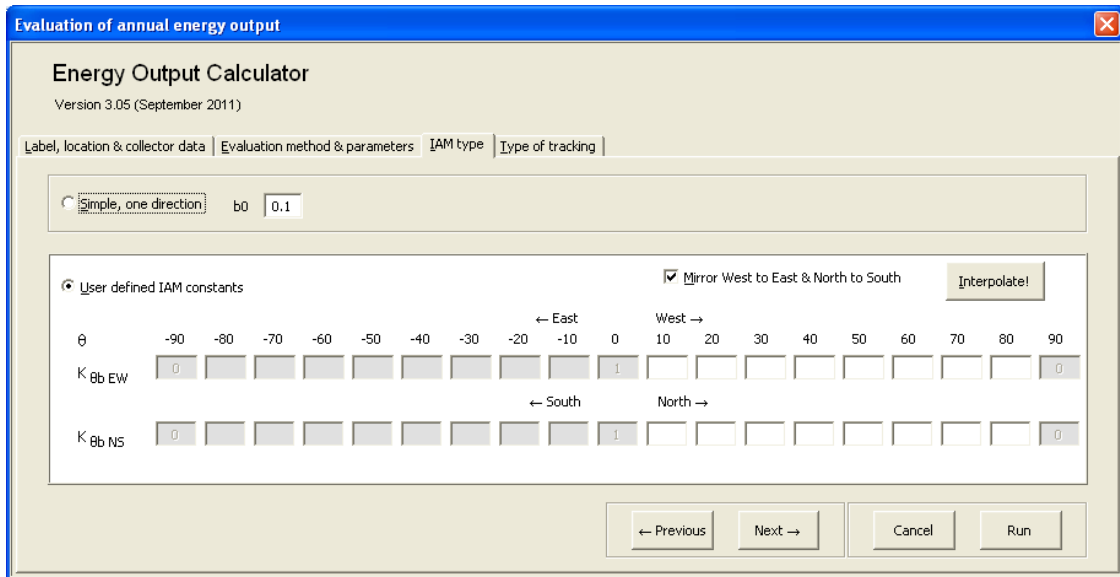


Figure 5. Information on IAM type (Incidence Angle Modifier).

**Important NOTE!:** The solar geometric incidence angle directions Longitudinal=NS and Transversal=EW are fixed independent of collector design and collector mounting/rotation.

The user makes the input of  $K_{\theta_{Lcoll}}$  and  $K_{\theta_{Tcoll}}$  on the input rows above for  $K_{\theta_{b\_EW}}$  and  $K_{\theta_{b\_NS}}$  according to how the collector is mounted when it's in operation. Related to the collector design  $\theta_{Lcoll}$  and  $\theta_{Tcoll}$  directions and angles are defined as  $\theta_{Tcoll}$ =Incidence angle projected on a plane perpendicular to the collector optical axis and  $\theta_{Lcoll}$ =Incidence angle projected on a plane parallel to the collector optical axis.  $K_{\theta_{Lcoll}}$  and  $K_{\theta_{Tcoll}}$  should follow the collector rotation if the vacuum tubes or reflectors are mounted horizontally or vertically.

Examples: "Horizontal" vacuum tubes directed EW will have its  $K_{\theta_{Lcoll}}$  values input as  $K_{\theta_{b\_EW}}$  and  $K_{\theta_{Tcoll}}$  input as  $K_{\theta_{b\_NS}}$ . "Vertical" vacuum tubes directed NS will have its  $K_{\theta_{Lcoll}}$  values input as  $K_{\theta_{b\_NS}}$  and  $K_{\theta_{Tcoll}}$  input as  $K_{\theta_{b\_EW}}$ . A collector with an asymmetrical IAM which performs better in the morning and in winter time than in the afternoon and in summer should thus have the higher  $K_{\theta_{b\_EW}}$  values to the left and the higher  $K_{\theta_{b\_NS}}$  values to the left.

In case of a collector plane with an azimuth not oriented to the south the indices EW and NS has to be interpreted as EW=Horizontally and NS=Vertically. The collector test results also have to be presented with  $K_{\theta_{Lcoll}}$  and  $K_{\theta_{Tcoll}}$  and  $\theta_{Lcoll}$  and  $\theta_{Tcoll}$  well defined and checked to avoid mistakes when using the values.

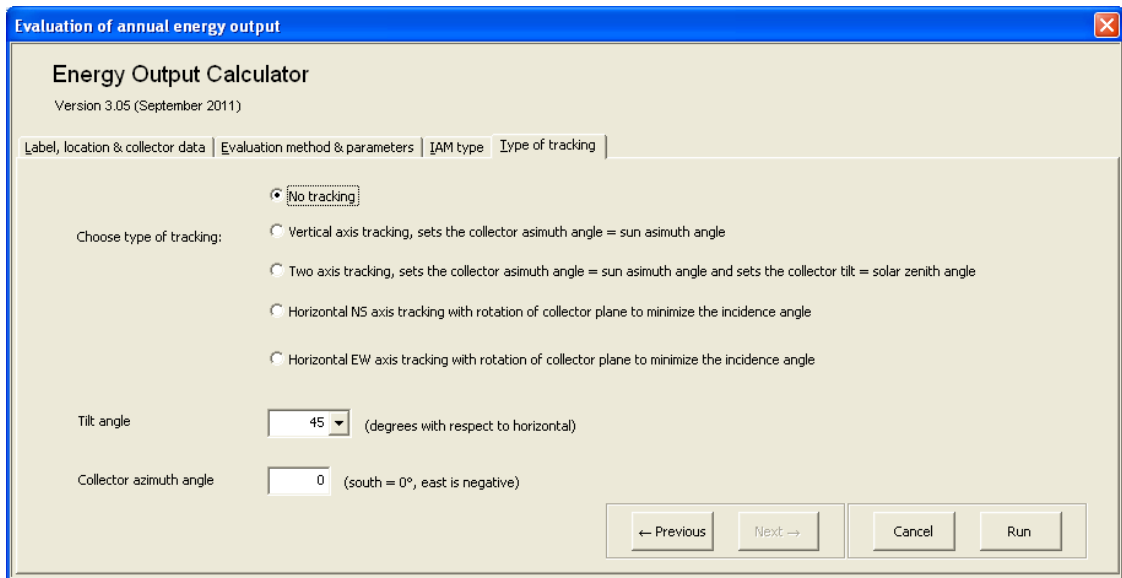


Figure 6. Type of tracking.

## Calculations

All calculations are made by the VBA code in Excel. The main idea is to have a transparent tool, so that anyone can check the code and the equations and that future updates can be easily implemented. Calculations are made with one hour time step and resolution of the climatic data. Details about the calculations are described in Appendix B, “Description of the calculations”.

## Results

Hour by hour results are written in a hidden worksheet. These data are then summarised as monthly data in the worksheet “Result” and in the chart “Figure”. For transparency, the hidden worksheets can be accessed if further information is requested. This is done by:

*Excel 2003:*

“Format\Sheet\Unhide” and choose to display the sheets “Result (hidden)” or “SS to QDT calc”. See “Example from the output sheet” in Appendix A.

*Excel 2007:*

Right click any tab in the lower left corner of the screen (“start...results...figure”) choose “unhide” and select the sheet you want to unhide.

## Appendices

The appendices include the following subchapters and have a numbering of their own.

- A. Example from the output sheet
- B. Description of the calculations
- C. Short explanation of input parameters and description of output data
- D. Interpolation of IAM type parameters
- E. Nomenclature

## References

- [1] McIntire, W.R. and K.A. Reed, Orientational relationships for optically non-symmetric solar collectors. *Solar Energy*, 1983. **31**(4): p. 405-410.
- [2] European Standard EN 12975-2:2006. Thermal solar systems – Solar collectors – Part 2: Test methods
- [3] SP-method 2709, Calculation of annual energy gain from solar collectors (in Swedish), Edition 3, 2008-09-19
- [4] Braun, J.E. and Mitchell, J.C. Solar Geometry for fixed and tracking surfaces. *Solar Energy* 1983 Vol 31 No 5 pp. 439-444.
- [5] Duffie, J.A. and Beckman W.A. *Solar Engineering of Thermal Processes* (2006)
- [6] TRNSYS 14.2 manual. Klein 1996
- [7] Personal communication and unpublished SOLNET material Michel Haller SPF
- [8] Fischer S., Heidemann W., Müller-Steinhagen H., Perers B., Bergquist P., Hellström B. Collector test method under quasi dynamic conditions according to the European Standard EN 12975-2. *Solar Energy*. Vol 76 pp 117-123 (2004)
- [9] Theunissen P.H., Beckman W.A. Solar transmittance characteristics of evacuated tubular collectors with diffuse back reflectors. *Solar Energy*, Vol 35, No. 4, pp. 311-320. (1985)
- [10] Pettersson, U. Kovacs, P. Perers, B. Improving the compatibility between Steady State and Quasi Dynamic testing for new collector designs. ISES 2009.

Appendix

**A. Example from the output sheet**

<b>Results from the Energy Output Calculator</b>				
<i>Version 3.05 (September 2011)</i>				
Identification label for the solar collector: Not specified				
Date of evaluation: 13 September, 2011				
<b>Monthly irradiance and yield per collector unit (kWh)</b>				
	Irradiance	Yield (three collector mean temperatures)		
		25°C	50°C	75°C
January	58	10	2	0
February	128	29	10	1
March	261	85	49	21
April	336	115	64	29
May	421	162	95	46
June	422	179	113	59
July	407	184	113	61
August	368	166	103	53
September	273	115	70	38
October	148	46	23	8
November	59	12	4	1
December	34	4	0	0
<b>Year</b>	<b>2 915</b>	<b>1 107</b>	<b>645</b>	<b>316</b>

<b>Location:</b>	Stockholm
<b>Longitude:</b>	-18.08
<b>Latitude:</b>	59.35
<b>Climate data, time period:</b>	1996-2005

**Collector information** (all inputs are based on aperture)

Aperture area: 2.5 m<sup>2</sup>

Evaluation method: Quasi Dynamic Testing

$F'(\tau \alpha)_{en}$	0.7	
$K_{\theta, d}$	1.0	( $\Rightarrow \eta_0 = F'(\tau \alpha)_{en} \cdot (K_{\theta, b}(15^\circ) \cdot 0.85 + K_{\theta, d} \cdot 0.15) = 0.698$ )
$c_1$	3.0 W/m <sup>2</sup> K	$\Rightarrow a_1 = c_1 + 3 \cdot c_3 = 3.6 \text{ W/m}^2\text{K}$ (including wind 3 m/s)
$c_2$	0.015 W/m <sup>2</sup> K <sup>2</sup>	$\Rightarrow a_2 = c_2 = 0.015 \text{ W/m}^2\text{K}^2$
$c_3$	0.2 J/m <sup>3</sup> K	
$c_4$	0.5 [--]	
$c_6$	0.05 s/m	

wind correction 0.5

Type of tracking: No tracking

Tilt angle: 45°

IAM Type: Simple, one-direction

$b_0 = 0.1$

**Figure 7. Example of results shown in the sheet “Result”**



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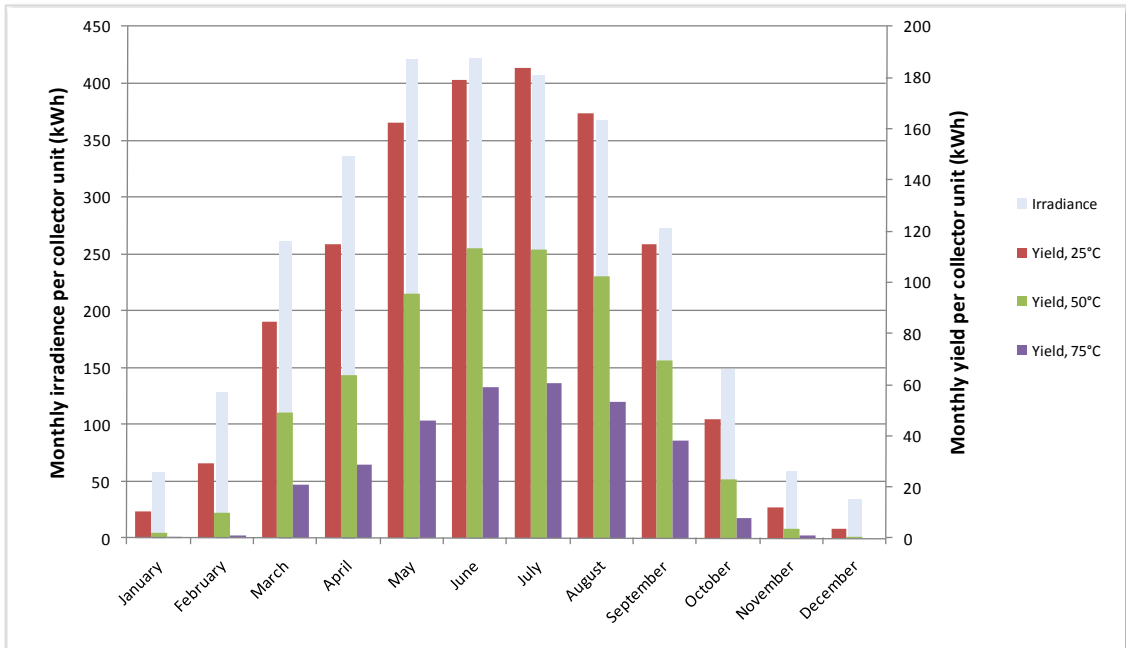


Figure 8. Example of "Figure" output.

## B. Description of the calculations

### Calculation of the heat output per time step (1 hour)

#### The extended collector model in accordance with EN12975

Using a similar notation as in ref [8] for the collector equation in EN12975 and adding the accepted simplified terms for unglazed collectors, we derive the full dynamic collector model for power output per m<sup>2</sup> of collector:

$$Q_t/A_a = F'(\tau\alpha)_{en} K_{\theta b}(\theta_L, \theta_T) G_{bT} + F'(\tau\alpha)_{en} K_{\theta d} G_{dT} - c_6 0.5 w_{coll} G_T - c_1 (t_m - t_a) - c_2 (t_m - t_a)^2 - c_3 0.5 w_{coll} (t_m - t_a) + c_4 (E_L - \sigma T_a^4) - c_5 dt_m/d\tau \quad (\text{Eq. 1})$$

The factor 0.5 accounts for the fact that wind speed data are normally recorded at 10 meters above ground level. Thus it is here assumed that true wind speed at ground level is 50% of that at 10 meters height.

The thermal capacitance correction term is used and derived in the QDT method but it is marked in grey as it was decided to leave this correction factor out in this version of the calculation tool. The influence on the annual performance figures is limited and similar for most normal collector designs.

#### Variables in equation 1:

$G_{bT}$ = beam solar radiation in the collector plane	[W/m <sup>2</sup> ]
$G_{dT}$ = diffuse solar radiation in the collector plane	[W/m <sup>2</sup> ]
$G_T$ = total (beam + diffuse) solar radiation in the collector plane	[W/m <sup>2</sup> ]
$\theta_{sunNS}$ , $\theta_{sunEW}$ = Incidence angles for beam radiation projected onto the north-south and east-west planes.	[Degrees]
$w_{coll}$ = wind speed in the collector plane	[m/s]
$t_m = (t_{in} + t_{out}) / 2$ = 0.5 mean fluid temp. between inlet and outlet of the collector	[°C]
$E_L$ = long wave or thermal radiation (incident from sky + ambient) in the collector plane	[W/m <sup>2</sup> ]
$T_a$ = ambient temperature close to the collector (in the shade) (Kelvin is only for thermal radiation calculations)	[K]
$t_a$ = ambient temperature close to the collector (in the shade)	[°C]
$\tau$ = time step in measurements and simulation.	[s]

#### Parameters in equation 1:

$F'(\tau\alpha)_{en}$ = zero loss efficiency of the collector, at normal incidence	[-]
$K_{\theta b}(\theta_{sunNS}, \theta_{sunEW})$ = incidence angle modifier for beam solar radiation.	[-]

$K_{\theta b}$  varies with incidence angle  $\theta_i$  (when a simple one direction  $b_0$  function is used) or with  $\theta_{sunNS}$  and  $\theta_{sunEW}$  (when user defined IAM constants are used).

$K_{\theta b\_EW}$  or  $K_{\theta b\_NS}$  are then calculated according to (Eq. 5).

$K_{\theta d}$ = incidence angle modifier for diffuse solar radiation (assumed to be a fixed value for each collector design). This value can be	[-]
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either determined experimentally in a dynamic test or integrated from beam incidence angle modifier curves ref [10].

$c_1$ = heat loss coefficient at $(t_m - t_a) = 0$ , $c_1$ is equal to $a_1$	[W/(m <sup>2</sup> K)]
$c_2$ = temperature dependence in the heat loss coefficient equal to $a_2$	[W/(m <sup>2</sup> K <sup>2</sup> )]
$c_3$ = wind speed dependence of the heat losses equal to $F'U_{wind}$	[J/(m <sup>3</sup> K)]
$c_4$ = long wave irradiance dependence of the heat losses, equal to $F'\epsilon$	[-]
$c_5$ = effective thermal capacitance, equal to $(mC)_e$	[J/(m <sup>2</sup> K)]
$c_6$ = wind dependence of the collector zero loss efficiency	[s/m]

If the collector performance is measured according to the Steady State method (EN 12975-2, chapter 6.3) there are no values for  $F'(\tau\alpha)_{en}$  and  $K_{\theta d}$  available. Still, these parameters can be calculated by integration of the incidence angle modifier for direct irradiance determined in a steady state test and from the zero-loss coefficient  $\eta_0$ . This calculation is performed in an independent hidden sheet called "SS to QDT calc".

Negative values of  $Q_t/A$  are not meaningful and therefore set to 0 in each particular time step.

The annual energy gain per m<sup>2</sup> of collector at the preset temperature  $t_m$  is equal to the sum of the mean heat output of all time steps.

$$Q/A_a = \Sigma (Q_t / A_a \cdot t) \text{ [kWh/m}^2\text{]} \quad (\text{Eq. 2})$$

The annual energy output at temperature  $t_m$  for example 50°C, is then multiplied with the collector *module* aperture area ( $A_a$ ) and reported as module output  $Q_{module}$ . Thus:

$$Q_{module} = Q/A_a \cdot A_a \text{ [kWh]} \quad (\text{Eq. 3})$$

### Calculation of incidence angle modifier $K_{\theta b}(\theta_i)$

The incidence angle modifier  $K_{\theta b}(\theta_i)$  is calculated differently depending on the type of collector. In this version of the excel tool the user can choose between 2 types of IAM depending on the type of solar collector.

1. "Simple, one direction": Typical flat plate collector with a plain incidence angle modifier irrespective of direction (transversally or longitudinally). The incidence angle modifier is calculated according to (Eq. 4).
2. "User defined": Collectors with a complex incidence angle modifier. The tool is developed to calculate both bi-axially (different IAM transversally and longitudinally) and multi-axially dependence (i.e. where the incidence angle modifier vary differently in the direction of east and west or north and south). Vacuum tubes with circular absorber have a Bi-axial dependence. Multi-axially or asymmetric dependence comes with, for example, some collectors with reflectors that are designed to reduce overheating in summer.

In the two models, when  $\theta_i$  is less than -90 and equal or greater than 90,  $K_{\theta b}(\theta)$  is set to 0. Per definition  $K_{\theta b}(\theta_i)$  is 1 at normal incidence to the collector ( $\theta_i = 0$ ) and  $K_{\theta b}(\theta_i)$  is 0 at 90 degrees ( $\theta_i = 90$ ). In the two models, this definition ( $|\theta_i| > 90$  degrees) can be used to determine if the sun is behind the collector plane and  $K_{\theta b}(\theta_i)$  should be set to 0.

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**Calculations of incidence angle modifier****”Simple one directional incidence angle modifier. Case 1 above”**

$$K_{\theta_b}(\theta_i) = 1 - b_0 \cdot (1/\cos \theta_i - 1) \quad (\text{Eq. 4})$$

**”User defined. Case 2 above”**

From the user input, a linear interpolation of the  $K_{b,i}$  value is made between the angles closest to the given one. For example, if the angle is  $73^\circ$ , the  $K_b$ -value is calculated as (both Transversal and Longitudinal):

$$K_{\theta_b,i}(73^\circ) = (70^\circ - 73^\circ) / (70 - 80) \cdot [(K_{\theta_b,i}(80^\circ) - K_{\theta_b,i}(70^\circ))] + K_{\theta_b,i}(70^\circ) \quad (\text{Eq. 5})$$

$$K_{\theta_b,i} = K_{\theta_b\_EW} \text{ or } K_{\theta_b\_NS}$$

$$K_{\theta_b}(\theta_i) = K_{\theta_b\_EW} \cdot K_{\theta_b\_NS} \quad (\text{Eq. 6})$$

**Calculations of solar incidence angles  $\theta_i$ ,  $\theta_{\text{sunEW}}$  and  $\theta_{\text{sunNS}}$  onto a collector plane**

The equations to calculate the position of the sun and the incidence angle to the collector surface are presented below. The nomenclature and equations follow the ones in the text book Duffie and Beckman (edition 2006) [5], as closely as possible. Solar time is corrected for the longitude shift from the local time zone and equation of time E (minutes) and to the mean solar time for the time step (therefore -0.5 hour below).

$$\text{Solar\_time} = ((\text{hour\_day} - 0.5) \cdot 3600 + E \cdot 60 + 4 \cdot (\text{STD\_longitude} - \text{longitude}) \cdot 60) / 3600 \quad \text{ref [5] [hours]} \quad (\text{Eq. 7})$$

$$E = 229.2 \cdot (0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B - 0.014615 \cdot \cos(2B) - 0.04089 \cdot \sin(2B)) \quad \text{ref [5] [minutes]} \quad (\text{Eq. 8})$$

$$B = (\text{day\_of\_year} - 1) \cdot 360 / 365 \quad \text{ref [5]} \quad (\text{Eq. 9})$$

$$\delta = 23.45 \cdot \sin(360 \cdot (284 + \text{day\_of\_year}) / 365) \quad \text{ref [5]} \quad (\text{Eq. 10})$$

Hour angle

$$\omega = -180 + \text{Solar\_time} \cdot 180 / 12 \quad (\text{Eq. 11})$$

Solar Zenith angle

$$\theta_Z = \arccos(\cos \phi \cdot \cos \omega \cdot \cos \delta + \sin \phi \cdot \sin \delta) \quad \text{ref [5]} \quad (\text{Eq. 12})$$

Solar azimuth from south, south=0 east= -90 west=90

$$\gamma_s = \text{SIGN}(\omega) \cdot \arccos [(\cos \theta_Z \sin \phi - \sin \delta) / (\sin \theta_Z \cos \phi)] \quad \text{ref [5]} \quad (\text{Eq. 13})$$

$\text{SIGN}(\omega) = 1 \text{ if } \omega > 0 \text{ and } -1 \text{ if } \omega < 0$

If  $\theta_Z < 90$  and  $\theta_i < 90$  then

$$\theta_{\text{sunEW}} = \arctan [\sin \theta_Z \cdot \sin (\gamma_s - \gamma) / \cos \theta_i] \quad \text{ref. [9]} \quad (\text{Eq. 14})$$

( $>0$  means to the “west” of collector normal)

Else

$$\theta_{\text{sunEW}} = 90$$

If  $\theta_Z < 90$  and  $\theta_i < 90$  then

$$\theta_{\text{sunNS}} = -(\arctan [\tan \theta_Z \cdot \cos (\gamma_s - \gamma)] - \beta) \quad \text{ref. [9]} \quad (\text{Eq. 15})$$

( $>0$  means to the “north” of collector normal)

Else

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$$\theta_{\text{sunNS}} = 90$$

Incidence angle between the direction of the sun and collector normal for all orientations of the collector, with tilt  $\beta$  and azimuth  $\gamma$

$$\theta_i = \arccos[\cos \theta_z \cdot \cos \beta + \sin \theta_z \cdot \sin \beta \cdot \cos (\gamma_s - \gamma)] \quad \text{ref [5]} \quad (\text{Eq. 16})$$

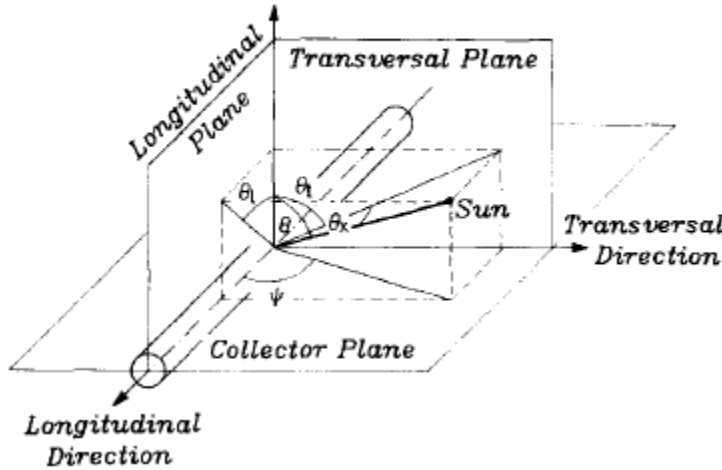


Figure 9 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

**Calculation of solar radiation onto a tilted collector plane with free orientation  
Tilt  $\beta$  and Azimuth  $\gamma$  including tracking surfaces.**

The notation  $G_{\text{horis}}$ ,  $G_{\text{b\_horis}}$  and  $G_{\text{d\_horis}}$  are used for total, beam and diffuse solar radiation onto a horizontal surface.  $G_{\text{bn}}$  is the beam radiation in direction to/from the sun. The notation  $G_o$  is used for extraterrestrial solar radiation on horizontal surface.

The total radiation on to a tilted collector plane  $G_T$  according to the Hay and Davies model can be written:

$$G_T = G_{\text{b\_horis}} \cdot R_b + G_{\text{d\_horis}} \cdot A_i \cdot R_b + G_{\text{d\_horis}} \cdot (1 - A_i) \cdot 0.5 \cdot (1 + \cos(\beta)) + G_{\text{horis}} \cdot \rho_g \cdot 0.5 \cdot (1 - \cos(\beta))$$

$$G_{\text{bT}} = G_{\text{b\_horis}} \cdot R_b \quad \text{and} \quad G_{\text{dT}} = G_T - G_{\text{bT}}$$

*Note that  $G_{\text{bT}}$  does not include the circumsolar diffuse radiation that most collectors, except high concentrating collectors, will accept as beam and the incidence angle modifier should work on this part too. This has to be investigated more but as this is the convention we propose this solution.*

$R_b = \cos(\theta_i) / \cos(\theta_z)$  is the conversion factor between the normal direction to the sun and the collector plane. Condition  $\theta_i < 90$  and  $\theta_z < 90$  else  $R_b = 0$

$A_i = G_{\text{b\_horis}} / G_o = \text{Anisotropy index (the fraction of the diffuse radiation which is circumsolar)}$

$\rho_g = \text{Ground albedo or ground reflection factor typically 0.1-0.3 but may be higher for snow}$

$G_o = 1367 \cdot (1 + 0.033 \cdot \cos(360 \cdot n / 365)) \cdot \cos(\theta_z)$

If  $G_{\text{horis}}$  and  $G_{\text{bn}}$  are given in the climate file  $G_{\text{b\_horis}} = G_{\text{bn}} \cdot \cos(\theta_z)$  and  $G_{\text{d\_horis}} = G_{\text{horis}} - G_{\text{b\_horis}}$  (this alternative gives higher accuracy at low solar altitudes and at high latitudes. But a solar collector is seldom in operation at these situation so for annual kWh it may be academic)

Note: One second order effect to consider here is that the second term (=circum solar radiation) in the  $G_T$  equation above should be added to the beam radiation in the collector

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plane for most collectors, also when calculating the output power. But for high concentrating collectors this circumsolar diffuse radiation may not be accepted as beam radiation and will miss the absorber. This is not explained fully in the simulation literature and needs some attention and further validation in special cases of high concentrating collectors. To be on the safe side the circum solar radiation should not be added to beam radiation in these cases.

### **Formulation of transformation of angles for fixed and tracking collector surfaces**

As the equations used for incidence angles onto the collector surface above are for arbitrary Tilt and Azimuth angles of the collector, it is quite easy to specify the basic tracking options:

1. Freely oriented but fixed collector surface with tilt  $\beta$  and azimuth  $\gamma$ , no eq. changes
2. Vertical axis tracking with fixed collector tilt  $\beta$ : set azimuth  $\gamma = \gamma_s$  all the time
3. Full two axes tracking: set collector tilt  $\beta = \theta_z + 0.001$  and collector azimuth  $\gamma = \gamma_s$  all the time.  $+0.001$  is to avoid division by zero in the equations of incidence angle.
4. Horizontal NS axis tracking with rotation of collector plane to minimize the incidence angle. Collector tilt angle  $\beta = \arctan(\tan(\theta_z) |\cos(\gamma - \gamma_s)|)$  and collector azimuth  $\gamma = -90$  if  $\gamma_s < 0$  and  $\gamma = 90$  if  $\gamma_s \geq 0$
5. Horizontal EW axis tracking with rotation of collector plane to minimize the incidence angle. Collector tilt angle  $\beta = \arctan(\tan(\theta_z) |\cos(\gamma_s)|)$  and collector azimuth  $\gamma = 0$  if  $|\gamma_s| < 90$  and  $\gamma = 180$  if  $|\gamma_s| \geq 90$

## Appendix

### C. Short explanation of input parameters and description of output data

#### Generally

All values for the collector in the calculations tool is based on the collector aperture area ( $A_a$ ). For the Swedish subsidy the energy output per module (gross area) is to be used. The calculated energy output is therefore to be multiplied with the aperture area of the collector and this value (C) together med the number of modules is written in to the subsidy form.

All numbers have to be entered with the “.” as the decimal separator. Also make sure that Windows uses “.” as the decimal separator. Try to always use 3 (three) significant figures for all inputs.

#### ”Collector information”

##### Measurements according to: Steady State (EN 12975-2, chapter 6.1)

These parameter inputs are used if the collector is measured according Steady State. In some cases collectors are measured according to Steady State but the results are given in terms of  $\eta_0$ ,  $a_1$  and  $a_2$ . In that case, the collector efficiency for beam and diffuse radiation ( $\eta_0$ ) is often weighted by 85% beam radiation at 15 degrees incidence angle and 15% diffuse radiation. If that is the case this alternative is a good approximation.

##### $\eta(0)$ , Zero-loss collector efficiency [-]

The parameter  $\eta_0$  is the collector efficiency when the mean collector temperature and the ambient temperature are equal. This refers also to a radiation at a right angle, no wind, and a division of beam and diffuse radiation of maximum 30% diffuse radiation.

##### $a_1$ , First order heat loss coefficient [ $W/m^2K$ ]

The collector efficiency depends on the difference between the collector mean temperature and the ambient temperature and decreases with higher over temperature in the collector. The coefficient  $a_1$  describes the first degree of temperature dependence of the heat losses from the collector in terms of  $W/m^2K$  and with a wind speed at 2-4 m/s.

##### $a_2$ , Second order heat loss coefficient [ $W/m^2K^2$ ]

The coefficient  $a_2$  describes the second degree of temperature dependence of the heat losses from the collector in terms of  $W/m^2K^2$ .

##### Tilt angle $\beta$ [degrees]

The desired collector tilt angle with respect to horizontal degrees i.e. 90 degrees is equal to vertical.

##### Measurements according to: Quasi Dynamic Testing (EN 12975-2, chapter 6.3)

This test method is giving the desired coefficients according to below.

##### $F'(\tau\alpha)_{en}$ , Collector optical efficiency for direct irradiance[-]

The parameter  $F'(\tau\alpha)_{en}$  is the collector efficiency when the mean collector temperature and the ambient temperature are equal. This refers also to a radiation at a normal incidence, no wind, and beam radiation.

##### $K_{\theta d}$ , Incidence angle modifier for diffuse radiation [-]

The diffuse irradiation is assumed to have a constant incidence angle modifier described by  $K_{\theta d}$  [- ]

## Appendix

*c1, First order heat loss coefficient [W/m<sup>2</sup>K]*

The collector efficiency depends on the difference between the collector mean temperature and the ambient temperature and decreases with higher over temperature in the collector. The coefficient  $c_1$  describes the first degree of temperature dependence of the heat losses from the collector in terms of W/m<sup>2</sup>K and without wind.

*c2, Second order heat loss coefficient [W/m<sup>2</sup>K<sup>2</sup>]*

The coefficient  $c_2$  describes the second degree of temperature dependence of the heat losses from the collector in terms of W/m<sup>2</sup>K<sup>2</sup>. Corresponds to  $a_2$  in the Steady State measurements.

*c3, Wind dependence of the heat loss coefficient [J/m<sup>3</sup>K]*

The coefficient  $c_2$  describes the wind dependence of the heat losses from the collector in terms of J/m<sup>3</sup>K. The coefficient  $c_1$ ,  $c_3$  and the wind speed corresponds to  $a_1$  trough  $a_1 = c_1 + u \cdot c_3$  where  $u$  is the actual wind speed. In the calculations a constant wind speed of 3 m/s is used.

*c4 Long wave irradiance dependence of the heat losses, equal to  $F' \varepsilon$  [-]**c6 Wind dependence of the collector zero loss efficiency [s/m]**Tilt angle [degrees]*

The desired collector tilt angle with respect to horizontal degrees i.e. 90 degrees is equal to vertical.

**”Distribution temperature”**

Refers to the mean temperature of the collector heat transfer fluid. The Swedish subsidy is based on a constant mean temperature of 50 °C and this version the variation is limited to a constant mean temperature of 25, 50 or 75°.

**”IAM Type”**

The incidence angle modifier can be defined in 2 different ways “Simple” or “User Defined”, as described below:

**”Simple”**

The incidence angle, for each angle, is characterized according to the equation:

$$K_{\text{ob}}(\theta_i) = 1 - b_0 \cdot (1/\cos \theta_i - 1)$$

Where  $b_0$  is a coefficient to describe the IAM,  $\theta$  is the angle against the collector surface and  $K_{\text{ob}}(\theta)$  is the value to multiply with the efficiency factor at the specific angle. The  $b_0$  is normally stated in the test report, but some given as i.e.  $K_{\text{ob}}(50)$ . The  $b_0$  then has to be calculated through eq. 4.

**”User defined”**

For some types of collectors the incidence angle modifier for every specific angle cannot be calculated according to a simple equation. The IAM then has to be presented by a table with the IAM for each angle. Under ”User defined” the IAM is to be stated for each angle in steps of 10 degrees both in east-west and north-south direction. For an upright positioned vacuum tube the east-west direction is equivalent to the transversal direction and the north-south direction is equivalent to the longitudinal. In most cases the IAM is symmetrical in the east-west direction and along the north-south direction. In the test report the values are given in a table but not always in every 10 degrees. In the excel tool all values have to be filled in. If some values are missing they have to be interpolated (compares to eq. 5). By definition the IAM value at the incidence angle 0 is 1.0 and 0 at 90 degrees.



## Appendix

### **Description of the output sheet**

The output sheet (se sheet "Result") presents the monthly energy output of the solar collector per aperture area ( $A_a$ ) at the constant temperatures of 25, 50 and 75°C. The monthly values are then summarised to an annual energy output at each temperature. As an output there is also a figure that shows the energy gain distribution over the year (see sheet "Figure").

The result sheet is also showing all the input parameters for the solar collector. As comparison the calculated values for  $F'(\tau\alpha)_{en}$  och  $K_{\theta d}$  are showed if the SS alternative is used.

## Appendix

### **D. Interpolation of IAM type parameters**

The ability to interpolate unknown IAM parameters has been included in version 3.05 of the program. A button is added above the area where the IAM parameters are entered.

When pressing the button, the empty boxes (in fact: the non-numeric boxes) are filled with interpolated values from the closest boxes with values. The algorithm used for this interpolation is described below.

- a. Check that there are values entered for  $-90^\circ$ ,  $0^\circ$  and  $90^\circ$ . If any of these boxes are empty a warning is shown and the interpolation is stopped.
- b. Retrieve all of the values in the boxes of the UserForm.
- c. Count the empty (non-numeric) boxes and save the indexes of them.
- d. Count the nodes (the numeric boxes used for the interpolation) and save the indexes of them.
- e. Loop through the nodes.
  - i. Calculate the linear equation.
  - ii. Fill the empty boxes with interpolated values using the linear equation.
  - iii. Repeat until all nodes (left-nodes) have been cycled.

Appendix

**E. Nomenclature**

<b>Term</b>	<b>Definition</b>	<b>Unit</b>
$a_1$	First degree of temperature dependence (Steady State)	$[\text{Wm}^{-2}\text{K}^{-1}]$
$a_2$	Second degree of temperature dependence (Steady State)	$[\text{Wm}^{-2}\text{K}^{-2}]$
$A_a$	Aperture area of the collector	$[\text{m}^2]$
$A_G$	Gross area of the collector	$[\text{m}^2]$
$b_o$	Constant for calculations of the incidence angle modifier	$[-]$
$c_1$	First degree of temperature dependence (Dynamic testing)	$[\text{Wm}^{-2}\text{K}^{-1}]$
$c_2$	Second degree of temperature dependence (Dynamic testing)	$[\text{Wm}^{-2}\text{K}^{-2}]$
$c_3$	Wind dependence of the heat loss coefficient (Dynamic testing)	$[\text{J}/\text{m}^3\text{K}]$
$c_4$	Long wave irradiance dep. of the heat losses, equal to $F'\epsilon$	$[-]$
$c_5$	Effective thermal capacitance, equal to $(mC)_e$	$[\text{J}/(\text{m}^2 \text{K})]$
$c_6$	Wind dependence of the collector zero loss efficiency	$[\text{s}/\text{m}]$
$F'$	Collector efficiency factor	$[-]$
$G^*$ or $G_T$	Global or Total irradiance in collector plane	$[\text{Wm}^{-2}]$
$G_{\text{horis}}$	Global or Total irradiance in horizontal plane	$[\text{Wm}^{-2}]$
$G_{b\_horis}$	Beam irradiance in horizontal plane	$[\text{Wm}^{-2}]$
$G_{d\_horis}$	Diffuse irradiance in horizontal plane	$[\text{Wm}^{-2}]$
$G_{bn}$	Beam irradiance in normal direction to the sun	$[\text{Wm}^{-2}]$
$G_o$	Extraterrestrial Radiation on horizontal plane	$[\text{Wm}^{-2}]$
$G_{bT}$	Beam irradiance in Tilted collector plane	$[\text{Wm}^{-2}]$
$G_{dT}$	Diffuse irradiance in Tilted collector plane	$[\text{Wm}^{-2}]$
$LT$	Local time	$[\text{h}]$
$K_{\theta b}(\theta_i)$	Incidence angle modifier for direct irradiance	$[-]$
$K_{\theta b\_EW}$	Incidence Angle Modifier (IAM) "EW" or "horizontally"	$[-]$
$K_{\theta b\_NS}$	Incidence Angle Modifier (IAM) "NS" or "vertically"	$[-]$
$K_{\theta L\text{coll}}$	Incidence Angle Modifier along the coll. tubes or reflectors.	$[-]$
$K_{\theta T\text{coll}}$	Incidence Angle Modifier <i>perpend. to coll. tubes or reflectors.</i>	$[-]$
$K_{\theta d}$	Incidence angle modifier for diffuse irradiance	$[-]$
$Q_t$	Mean power output during one time step	$[\text{W}]$
$Q/A_a$	Useful energy extracted from the collector per m <sup>2</sup>	$[\text{kWh}]$
$Q_{\text{module}}$	Useful energy extracted from the collector, annual energy gain	$[\text{kWh per module}]$
$t$	time step	$[\text{h}]$
$t_a$	Ambient air temperature	$[\text{°C}]$
$t_m$	Collector mean temperature	$[\text{°C}]$
$\theta_Z$	Solar Zenith angle ( $=90 - \theta_H$ )	
$\gamma_s$	Solar Azimuth angle ( 0 = south, east negative)	$[\text{degrees}]$
$\beta$	tilt angle of collector plane from horizontal	$[\text{degrees}]$
$\gamma$	Collector azimuth angle from south =0, east negative	$[\text{degrees}]$
$\delta$	Solar Declination	$[\text{degrees}]$
$\omega$	Solar hour angle	$[\text{degrees}]$
$\theta_i$	Angle of incidence onto collector. (from collector normal)	$[\text{degrees}]$
$\phi$	Latitude of collector and climate data location	$[\text{degrees}]$
$\theta_{L\text{sunNS}}$	Solar Incidence angle in a vertical NS plane to the collector	$[\text{degrees}]$
$\theta_{T\text{sunEW}}$	Solar Incidence angle in an EW plane perpendicular to the coll.	$[\text{degrees}]$
$\theta_{L\text{coll}}$	Incidence angle onto coll. along the vacuum tubes or reflectors	$[\text{degrees}]$
$\theta_{T\text{coll}}$	Incid. angle onto coll. perpendicular to vac. tubes or reflectors	$[\text{degrees}]$
$\eta_o$	Solar collector zero-loss efficiency at $(t_m - t_a) = 0$ based on global or total radiation $G_T$	$[-]$
$F'(\tau\alpha)_{\text{en}}$	Effective transmittance-absorptance product at $(t_m - t_a) = 0$	$[-]$

Appendix

for direct solar radiation  $G_{bT}$  at normal incidence.

<i>T</i>	Transversally to directions of vacuum tubes or reflectors	
<i>L</i>	Longitudinally along vacuum tubes and reflectors	
Hour_day	Time stamp in the Excel code during the day (first hour = 1.0)	[hours]
$L_{loc}=\text{Longitude}$	Longitude of location (e.g. Stockholm -18.080) <i>Angles east of Greenwich are negative</i>	[degrees]
$L_{std}=\text{STD\_longitude}$	Longitude of time zone (e.g. Sweden -15.0) <i>Angles east of Greenwich are negative</i>	[degrees]
<i>E</i>	Equation of time correcting for the eccentric path of the earth around the sun.	[minutes]
<i>B</i>	“Earth position” around the sun during the year 0-360 deg.	[degrees]
$n = \text{Day of year}$	Daynumber from the beginning of the year. (Jan 1 = 1)	[ - ]