

# Description of ScenoCalc (Solar Collector Energy Output Calculator), a program for calculation of annual solar collector energy output

File name: ScenoCalc v6.1.xlsm

## Introduction

This document summarises how to use ScenoCalc (Solar Collector 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 for test institutes and certification bodies to enable them to convert collector model parameters determined through standardized tests into energy performance figures. This is done in order to give the end-user a possibility to compare different types of solar collectors under different weather conditions. The program shall therefore not be used as a calculation tool for design of solar energy installations. No system is simulated in the tool. 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 WISC<sup>1</sup> collectors. The current version of the tool supports only solar thermal liquid heating collectors. PVT and air collectors will be added in a future release. The different combinations of calculation modes supported in the current version of the tool are shown in Table 1.

Table 1 Variety of evaluation options with ScenoCalc v6.1

	Steady state testing	Quasi dynamic testing
WISC collectors	✓	✓
One-directional IAM type	✓	✓
User-defined IAM type	✓	✓
Tracking mode 1–5	✓	✓

## System requirements

The calculation tool is constructed using Microsoft Excel 2010 (version 14.0) and Visual Basic 7.0. These versions should be used for evaluations, since the tool has not been tested using other versions of Excel and Visual Basic. Nevertheless, it may be possible to run the tool with other versions. Excel on Mac OS is currently not supported.

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<sup>1</sup> Wind and/or infrared sensitive collectors (WISC)

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## Description of the program

The scope of the program is to evaluate the annual energy output of flat plate collectors, evacuated tube collectors, concentrating collectors and WISC collectors. The evaluation can either be performed as “A. SK Certificate evaluation” or as “B. Basic evaluation”.

### Information flow

The user of ScenoCalc starts by pressing either the A or the B button in the *Start* sheet according to Figure 1.

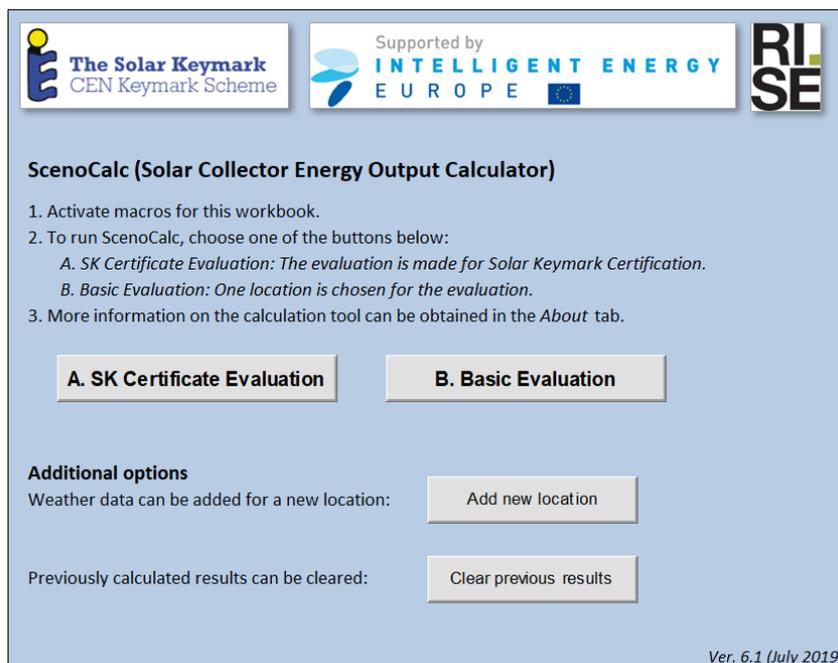


Figure 1. Main screen in ScenoCalc

When option A is chosen, data entry is managed through the Solar Keymark datasheets page 1 and 2, see Figure 2. When option B is chosen, data entry is managed through a number of tabs, see Figure 3 to Figure 7. When data has been entered, the monthly amount of heat that can be extracted from the solar collector is calculated. The results are presented in the datasheet page 2 for all four standard locations and for all sizes entered on page 1 of the data sheet (option A) or in a table and a graph for one location and one size (option B). 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. All hidden sheets can be unhidden without using a password.

### User input

When pressing the “**A. SK Certificate evaluation**” button the user is presented to the Solar Keymark datasheets which are used for entering the user input. These datasheets are self-explanatory.

When pressing the “**B. Basic 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 the locations Athens, Davos, Stockholm and Wurzburg and to temperatures ranging from 0°C to 100°C, see Figure 3. Location weather data is taken from a hidden sheet.



Evaluation of annual energy output

The Solar Keymark CEN Keymark Scheme INTELLIGENT ENERGY EUROPE RI SE

ScenoCalc (Solar Collector Energy Output Calculator)  
Ver. 6.1 (July 2019)

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

Choose test method:  
 Steady state (ISO 9806:2017, Ch. 23.4.2 & 23.4.4)  
 Quasi Dynamic Testing (ISO 9806:2017, Ch. 23.4.5)

n0, b: 0.80 [-] Based on gross area. a4: 0.2 [-]  
 Kθ,d: 0.9 [-] Diffuse angle modifier. a6: 0.05 [s/m]  
 a1: 3.00 [W/m²K] a7: 0.5 [W/m²K]  
 a2: 0.015 [W/m²K²] a8: 0.0000035 [W/m²K³]  
 a3: 0.2 [J/m²K]

← Previous Next → Cancel Run

Figure 4 Input of collector parameters for option B (Basic Evaluation)

After this the input on Incidence Angle Modifier (IAM) type and parameters are supplied, see Figure 5. Here, user input is required for all angles for proper calculation of annual energy output.

Evaluation of annual energy output

The Solar Keymark CEN Keymark Scheme INTELLIGENT ENERGY EUROPE RI SE

ScenoCalc (Solar Collector Energy Output Calculator)  
Ver. 6.1 (July 2019)

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

b0 fit (IAM at 50°)  Mirror West to East & North to South

User defined IAM constants Linear interpolation

	← East West →																		
$\theta_{iEW}$	-90°	-80	-70	-60	-50	-40	-30	-20	-10	0°	10	20	30	40	50	60	70	80	90°
$K_{\theta bEW}$	0	0.69	1.37	1.54	1.54	1.29	1.17	1.05	1.03	1	1.03	1.05	1.17	1.29	1.54	1.54	1.37	0.69	0

	← South North →																		
$\theta_{iNS}$	-90°	-80	-70	-60	-50	-40	-30	-20	-10	0°	10	20	30	40	50	60	70	80	90°
$K_{\theta bNS}$	0	0.37	0.73	0.87	0.94	0.97	0.99	1	1	1	1	1	0.99	0.97	0.94	0.87	0.73	0.37	0

← Previous Next → Cancel Run

Figure 5 Input screen for IAM type and parameters (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.

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. See also Figure 6.

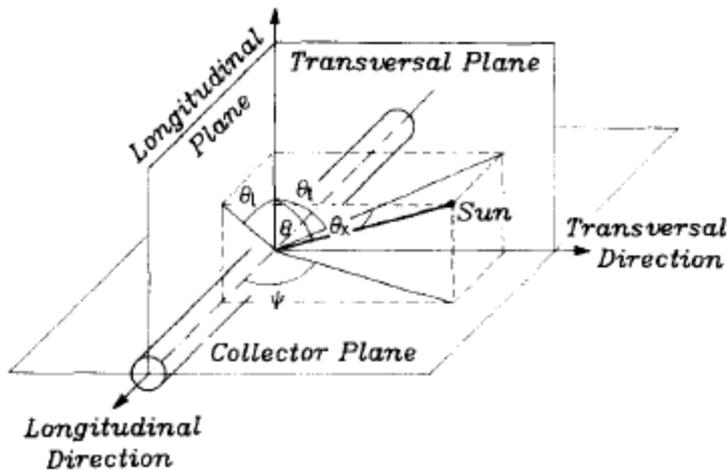


Figure 6 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

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  $K_{\theta_{b\_EW}}$ .

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. An “Interpolate” button is located 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 values interpolated from the values in the surrounding boxes.

Finally the type of tracking, azimuth and tilt angle is chosen (Figure 7) 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.

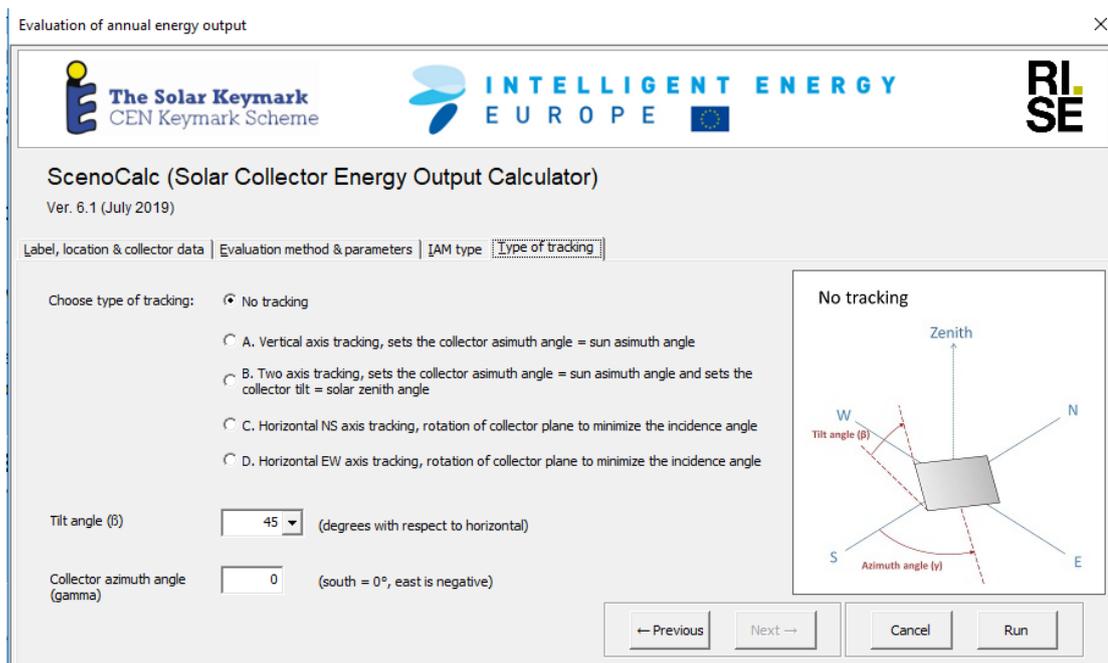


Figure 7 Type of tracking. For locations in the southern hemisphere set  $90 < \gamma < -90$ .

## 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 2007/2010:*

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 using option B (Basic evaluation)
- B. Description of the calculations
- C. Short explanation of input parameters and description of output data
- D. Interpolation of IAM type parameters
- E. Nomenclature

Appendix

**A. Example from the output sheet using option B (Basic evaluation)**



**Results from the ScenoCalc evaluation**

Ver. 6.1 (July 2019)

Identification label for the solar collector: Acompany (Abrand)

Date of evaluation: 12 August, 2019

Evaluation method: Quasi Dynamic Testing

**Thermal yield per collector module (kWh/module)**

	Total radiation	Yield for three collector mean temperatures		
		25°C	50°C	75°C
January	64	45	31	18
February	86	63	43	27
March	136	107	80	55
April	177	148	115	85
May	213	189	150	113
June	210	186	147	108
July	215	195	155	118
August	204	188	151	115
September	166	150	118	90
October	111	89	64	44
November	54	35	22	13
December	43	26	17	9
<b>Year</b>	<b>1680</b>	<b>1420</b>	<b>1094</b>	<b>793</b>

Location: Würzburg  
 Longitude: -9.95 (positive longitude = west of the prime meridian)  
 Latitude: 49.80  
 Time period for climate data: 1996-2005

**Collector parameters (based on the gross area)**

Gross area 1.35 m<sup>2</sup>  
 $\eta_{0b}$  0.900  
 $K_{e,d}$  0.900 ( $\Rightarrow \eta_0 = \eta_{0b}(0.85 + K_{e,d} \cdot 0.15) = 0.89$ )  
 $a_1$  3 W/m<sup>2</sup>K  
 $a_2$  0.015 W/m<sup>2</sup>K<sup>2</sup>  
 $a_3$  0.2 J/m<sup>2</sup>K<sup>2</sup>  
 $a_4$  0 -  
 $a_5$  0 s/m  
 $a_7$  0 W/m<sup>2</sup>K<sup>4</sup>  
 $a_8$  0 W/m<sup>2</sup>K<sup>4</sup>

Figure 8 Example of results shown in the sheet "Result"

### Appendix

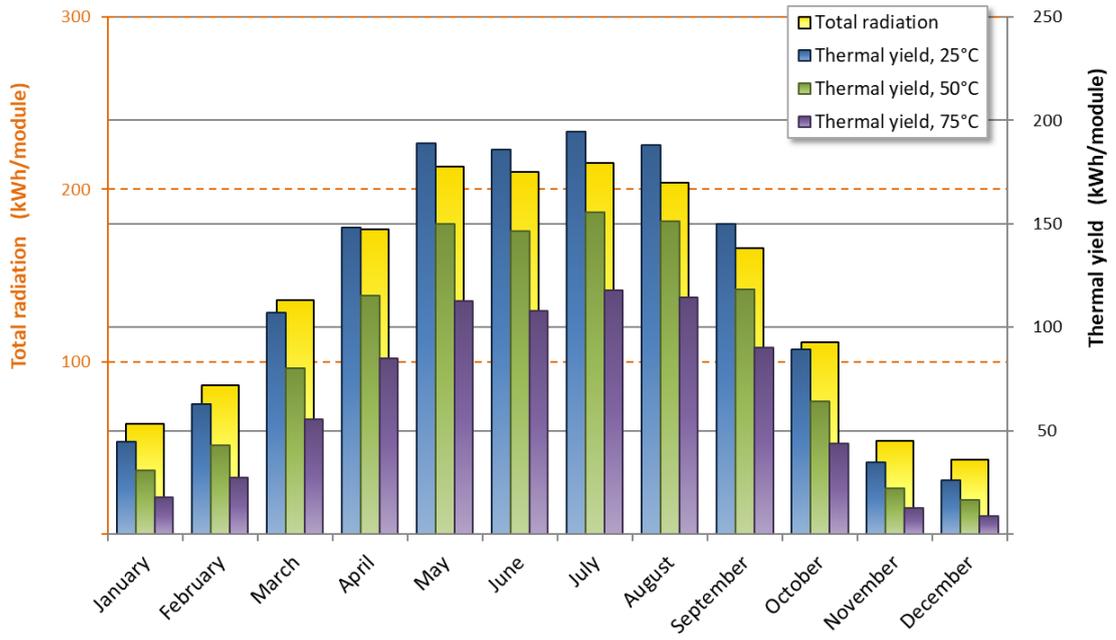


Figure 9 Example of graphical output

## Appendix

### B. Description of the calculations

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

The extended collector model in accordance with ISO 9806:2017 valid for both steady-state and quasi-dynamic testing is as follows

$$\dot{Q} = A_G \left[ \eta_{0,b} K_b(\theta_L, \theta_T) G_b + \eta_{0,b} K_d G_d - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_3 u'(\vartheta_m - \vartheta_a) + a_4(E_L - \sigma T_a^4) - a_5 \left( \frac{d\vartheta_m}{dt} \right) - a_6 u' G - a_7 u'(E_L - \sigma T_a^4) - a_8(\vartheta_m - \vartheta_a)^4 \right] \quad (1)$$

The thermal capacitance correction term,  $a_5$ , is left out in this version of the calculation tool. The influence of this term on the annual performance figures is limited and similar for most normal collector designs.

Variables in equation 1 are given below, see also Chapter 4 of ISO 9806:2017.

$A_G$	Gross area of collector as defined in the ISO 9488	$\text{m}^2$
$a_1$	Heat loss coefficient	$\text{W}/(\text{m}^2 \cdot \text{K})$
$a_2$	Temperature dependence of the heat loss coefficient	$\text{W}/(\text{m}^2 \cdot \text{K}^2)$
$a_3$	Wind speed dependence of the heat loss coefficient	$\text{J}/(\text{m}^3 \cdot \text{K})$
$a_4$	Sky temperature dependence of the heat loss coefficient	—
$a_5$	Effective thermal capacity	$\text{J}/(\text{m}^2 \cdot \text{K})$
$a_6$	Wind speed dependence of the zero loss efficiency	$\text{s}/\text{m}$
$a_7$	Wind speed dependence of IR radiation exchange	$\text{W}/(\text{m}^2 \cdot \text{K}^4)$
$a_8$	Radiation losses	$\text{W}/(\text{m}^2 \cdot \text{K}^4)$
$E_L$	Longwave irradiance ( $\lambda > 3 \mu\text{m}$ )	$\text{W}/\text{m}^2$
$G_b$	Direct solar irradiance (beam irradiance)	$\text{W}/\text{m}^2$
$G_d$	Diffuse solar irradiance	$\text{W}/\text{m}^2$
$K_b(\theta_L, \theta_T)$	Incidence angle modifier for direct solar irradiance	—
$K_d$	Incidence angle modifier for diffuse solar radiation	—
$Q$	Useful power extracted from collector	$\text{W}$
$u'$	Reduced surrounding air speed $u' = u - 3 \text{ m/s}$	$\text{m}/\text{s}$
$\eta_{0,b}$	Peak collector efficiency ( $\eta_b$ at $\vartheta_m - \vartheta_a = 0 \text{ K}$ ) based on beam irradiance, $G_b$	—
$\vartheta_a$	Ambient air temperature	$^{\circ}\text{C}$
$\vartheta_m$	Mean temperature of heat transfer fluid	$^{\circ}\text{C}$
$\sigma$	Stefan-Boltzmann constant	$\text{W}/(\text{m}^2 \cdot \text{K}^4)$

Negative power outputs are not meaningful and therefore set to 0 in each particular time step.

The annual energy gain per  $\text{m}^2$  of collector at the pre-set temperature  $\vartheta_m$  is equal to the sum of the mean heat output of all time steps.

## Appendix

$$\frac{Q}{A_G} = \sum_{t=0}^{t=8760} \frac{Q_t}{A_G} \cdot t$$

The annual energy output at temperature  $\vartheta_m$  for example 50°C, is then multiplied with the collector *module* gross area ( $A_G$ ) and reported as module output  $Q_{\text{modul}}$  [kWh] as

$$Q_{\text{module}} = \frac{Q}{A_G} A_G$$

### Calculation of Annual efficiency, $\eta_a$

On page 2 of option “A. SK Certification Evaluation” the annual efficiency is calculated as

$$\eta_a = \frac{CAO_{A_G}}{H_i}$$

where  $CAO_{A_G}$  is the annual collector output per collector gross area,  $A_G$ , for each modelled temperature level and  $H_i$  the annual irradiance for location “i”.

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

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°, the  $K_b$ -value is calculated as (both Transversal and Longitudinal):

$$K_{\theta b,i}(73^\circ) = \frac{(70^\circ - 73^\circ)}{(70^\circ - 80^\circ)} \cdot [K_{\theta b,i}(80^\circ) - K_{\theta b,i}(70^\circ)] + K_{\theta b,i}(70^\circ)$$

When  $\theta_i$  is 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° ( $\theta_i = 90^\circ$ ).

### 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)<sup>2</sup>, 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).

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

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

$$B = (\text{day\_of\_year} - 1) \cdot 360 / 365$$

$$\delta = 23.45 \cdot \sin(360 \cdot (284 + \text{day\_of\_year}) / 365)$$

Hour angle

$$\omega = -180 + \text{Solar\_time} \cdot 180 / 12$$

Solar Zenith angle

<sup>2</sup> Duffie, J. A. and Beckman W.A. Solar Engineering of Thermal Processes (2006)

Appendix

$$\theta_Z = \arccos(\cos \phi \cdot \cos \omega \cdot \cos \delta + \sin \phi \cdot \sin \delta)$$

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

$$\gamma_s = \text{SIGN}(\omega) \cdot | \arccos [(\cos \theta_Z \sin \phi - \sin \delta) / (\sin \theta_Z \cos \phi)] |$$

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

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

$$\theta_{\text{sunEW}} = \arctan [\sin \theta_Z \cdot \sin (\gamma_s - \gamma) / \cos \theta_i] \quad \text{ref. Theunissen et al: (1985)}^3$$

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

Else

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

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

$$\theta_{\text{sunNS}} = -(\arctan [\tan \theta_Z \cdot \cos (\gamma_s - \gamma)] - \beta) \quad \text{ref. Theunissen et al: (1985)}$$

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

Else

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

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

$$\theta_i = \arccos[\cos \theta_Z \cdot \cos \beta + \sin \theta_Z \cdot \sin \beta \cdot \cos (\gamma_s - \gamma)]$$

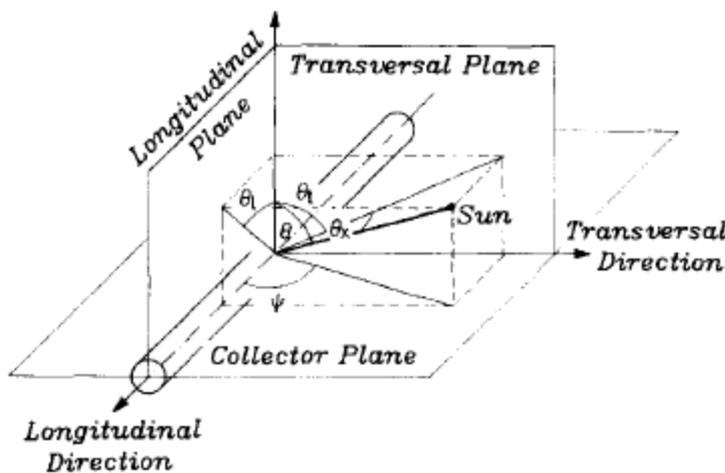


Figure 10 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

<sup>3</sup> 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)

## Appendix

**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  $G_0$  is used for extra-terrestrial 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:

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

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

*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  $R_b = 0$

$A_i = G_{\text{b\_horis}} / G_0 =$  Anisotropy index (the fraction of the diffuse radiation which is circumsolar)

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

$$G_0 = 1367 \cdot (1 + 0.033 \cdot \cos(360 \cdot n / 365)) \cdot \cos(\theta_z)$$

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 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**

Collector parameters in the calculations tool are based on collector gross area ( $A_g$ ). The calculated energy output is multiplied with the gross area of the collector and the output per module is then presented in the output sheet.

Always make sure to use the adequate number of decimal places as defined by Table A.6 of ISO 9806:2017.

#### **Collector information**

For details regarding each parameter input (see for example Figure 4), see ISO 9806:2017.

#### **Distribution temperature**

Refers to the mean temperature of the collector heat transfer fluid. As default, constant mean temperatures of 25, 50 or 75K are given. These can be changed when choosing evaluation option B.

**NB!** If “Maximum temperature difference during thermal performance test” on page 1 of option A is set to lower than -5, 20 or 45 the power and annual outputs for 25, 50 and 75K respectively will be set to “—” as the calculations are only valid for “Maximum temperature difference during thermal performance test” +30K according to the standard.

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

The output sheet (see sheet “Result”) presents the monthly energy output of the solar collector per aperture area ( $A_G$ ) at constant temperatures of 25, 50 and 75°C<sup>4</sup>. 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 Figure 9 for an example).

The result sheet is also showing all the input parameters for the solar collector.

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<sup>4</sup> Only valid if the “Maximum temperature difference during thermal performance test” on page 1 of option A +30K is not exceeded

## Appendix

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

The ability to interpolate unknown IAM parameters has been included from 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  $0^\circ$  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>Symbol</b>	<b>Definition</b>	<b>Unit</b>
$A_G$	Gross area of collector as defined in the ISO 9488	$m^2$
$a_1$	Heat loss coefficient	$W/(m^2 \cdot K)$
$a_2$	Temperature dependence of the heat loss coefficient	$W/(m^2 \cdot K^2)$
$a_3$	Wind speed dependence of the heat loss coefficient	$J/(m^3 \cdot K)$
$a_4$	Sky temperature dependence of the heat loss coefficient	—
$a_5$	Effective thermal capacity	$J/(m^2 \cdot K)$
$a_6$	Wind speed dependence of the zero-loss efficiency	$s/m$
$a_7$	Wind speed dependence of IR radiation exchange	$W/(m^2 \cdot K^4)$
$a_8$	Radiation losses	$W/(m^2 \cdot K^4)$
$b_u$	Collector efficiency coefficient (wind dependence)	$s/m$
$C$	Effective thermal capacity of collector	$J/K$
$CR$	Geometric concentration ratio	—
$c_f$	Specific heat capacity of heat transfer fluid	$J/(kgK)$
$c_{f,i}$	Specific heat capacity of heat transfer fluid at the collector inlet	$J/(kgK)$
$c_{f,e}$	Specific heat capacity of heat transfer fluid at the collector outlet	$J/(kgK)$
$c_{f,a}$	Specific heat capacity of the ambient air	$J/(kgK)$
$E_L$	Longwave irradiance ( $\lambda > 3 \mu m$ )	$W/m^2$
$G_{hem}$	m Hemispherical solar irradiance	$W/m^2$
$G_S$	Hemispherical solar irradiance for the calculation for the standard stagnation temperature	$W/m^2$
$G_m$	Average measured hemispherical solar irradiance	$W/m^2$
$G''$	Net irradiance	$W/m^2$
$G_b$	Direct solar irradiance (beam irradiance)	$W/m^2$
$G_d$	Diffuse solar irradiance	$W/m^2$
$H$	Irradiation on collector plane for exposure test	$MJ/m^2$
$K_{hem}(\theta_L, \theta_T)$	Incidence angle modifier for hemispherical solar radiation	—
$K_b(\theta_L, \theta_T)$	Incidence angle modifier for direct solar irradiance	—
$K\theta_L$	Incidence angle modifier in the longitudinal plane	—
$K\theta_T$	Incidence angle modifier in the transversal plane	—
$K_d$	Incidence angle modifier for diffuse solar radiation	—
$m$	Mass flow rate of heat transfer fluid	$kg/s$
$m_{min}$	Minimum mass flow by the performance test	$kg/h$

## Appendix

Symbol	Definition	Unit
$m_{\max}$	Maximum mass flow by the performance test	kg/h
$m_e$	Downstream air mass flow rate	kg/s
$m_i$	Upstream air mass flow rate	kg/s
$m_l$	Leakage air mass flow rate	kg/s
$p_{f,e}$	Static pressure of the heat transfer fluid (air) at the outlet of the solar collector	Pa
$p_{f,i}$	Static pressure of the heat transfer fluid (air) at the inlet of the solar collector	Pa
$p_{\text{abs}}$	Absolute pressure of the ambient air	Pa
$Q$	Useful power extracted from collector	W
$Q_{\text{peak}}$	Peak power. Power output of the collector for normal incidence, $G_b = 850 \text{ W/m}^2$ , $G_d = 150 \text{ W/m}^2$ and $\vartheta_m - \vartheta_a = 0 \text{ K}$	W
$R_D$	Gas constant for water vapour	461.4 J/(kgK)
$R_L$	Gas constant for air	287.1 J/(kgK)
$T$	Absolute temperature	K
$t$	Time	s
$u$	Surrounding air speed	m/s
$u'$	Reduced surrounding air speed $u' = u - 3 \text{ m/s}$	m/s
$U$	Measured overall heat loss coefficient of collector with reference to $(\vartheta_m - \vartheta_a)/G_{\text{hem}}$	W/(m <sup>2</sup> K)
$V_f$	Fluid capacity of the collector	m <sup>3</sup>
$V$	Volumetric flow	m <sup>3</sup> /s
$V_e$	Volumetric flow at the outlet of the solar collector	m <sup>3</sup> /s
$V_i$	Volumetric flow at the inlet of the solar collector	m <sup>3</sup> /s
$V_l$	Volumetric leakage flow rate	m <sup>3</sup> /s
$X_{W,a}$	Water content of the ambient air	kg H <sub>2</sub> O/kg dry air
$X_{W,e}$	Water content of the air at the exit of the solar collector	kg H <sub>2</sub> O/kg dry air
$X_{W,i}$	Water content of the air at the inlet of the solar collector	kg H <sub>2</sub> O/kg dry air
$\Delta p$	Pressure difference between fluid inlet and outlet	Pa
$\Delta t$	Time interval	s
$\Delta T$	Temperature difference between fluid outlet and inlet ( $\vartheta_e - \vartheta_{in}$ )	K
$\gamma$	Solar azimuth angle	°
$\eta_b$	Collector efficiency based on beam irradiance $G_b$	—
$\eta_{\text{hem}}$	Collector efficiency based on hemispherical irradiance $G_{\text{hem}}$	—
$\eta_{0,b}$	Peak collector efficiency ( $\eta_b$ at $\vartheta_m - \vartheta_a = 0 \text{ K}$ ) based on	—

## Appendix

Symbol	Definition	Unit
	beam irradiance $G_b$	
$\eta_{0, \text{hem}}$	Peak collector efficiency ( $\eta_{0, \text{hem}}$ at $\vartheta_m - \vartheta_a = 0$ K) based on hemispherical irradiance $G_{\text{hem}}$	—
$\eta_{\text{hem, mi}}$	Collector efficiency, with reference to mass flow $m_i$	—
$\theta$	Angle of incidence	°
$\theta_L$	Longitudinal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the longitudinal plane	°
$\theta_T$	Transversal angle of incidence: angle between the normal to the plane of the collector and incident sunbeam projected into the transversal plane	°
$\vartheta_a$	Ambient air temperature	°C
$\vartheta_{\text{am}}$	Measured ambient air temperature	°C
$\vartheta_{\text{as}}$	Ambient air temperature for the standard stagnation temperature	°C
$\vartheta_e$	Collector outlet temperature	°C
$\vartheta_i$	Collector inlet temperature	°C
$\vartheta_m$	Mean temperature of heat transfer fluid	°C
$\vartheta_{\text{max\_op}}$	Maximum operating temperature	°C
$\vartheta_{\text{stg}}$	Standard stagnation temperature	°C
$\vartheta_{\text{sky}}$	Atmospheric or sky temperature	°C
$\vartheta_{\text{trigger}}$	Trigger temperature for safety activation	°C
$\vartheta_{\text{m,th}}$	Volume flow weighted mean temperature	°C
$\vartheta_{\text{mp,e}}$	Fluid temperate at the downstream air mass flow meter	°C
$\vartheta_{\text{mp,i}}$	Fluid temperate at the upstream air mass flow meter	°C
$\vartheta_{\text{sm}}$	Average measured absorber temperature	°C
$\lambda$	Wave length	$\mu\text{m}$
$\rho$	Density of heat transfer fluid	$\text{kg}/\text{m}^3$
$\rho_l$	Density of air	$\text{kg}/\text{m}^3$
$\sigma$	Stefan-Boltzmann constant	$\text{W}/(\text{m}^2\text{K}^4)$
$\tau_c$	Collector time constant	s
$\tau$	Transmittance	—
$(\tau\alpha)$	Effective transmittance-absorptance product	—