

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

File name: ScenoCalc v4.04 - locked/unlocked.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 and independently of which of the two EN 12975 collector performance test methods that were used during testing. 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 unglazed 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 the table below:

	Steady state testing	Quasi dynamic testing
Unglazed collectors	✗	✓
One-directional IAM type	✓	✓
User-defined IAM type	✓	✓
Asymmetric IAM constants (E-W and N-S) <sup>1</sup>	✗	✓
Tracking mode 1-5	✓	✓

## System requirements

The calculation tool is constructed using Microsoft Excel 2010 (version 14.0) and Visual Basic 6.3. 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.

---

<sup>1</sup> The IAM constants can be multi-axial (asymmetrically for east-west and for north-south respectively) for Quasi dynamic testing, whereas only fully symmetrical or bi-axial constants are allowed for Steady state testing.

## Table of contents

<b>Introduction</b>	<b>1</b>
<i>System requirements</i>	1
<b>Description of the program</b>	<b>3</b>
<i>Information flow</i>	3
<i>User input</i>	3
<i>Calculations</i>	7
<i>Results</i>	7
<b>Appendices</b>	<b>8</b>
<b>References</b>	<b>9</b>
<b>A. Example from the output sheet using option A (Basic evaluation)</b>	<b>10</b>
<b>B. Description of the calculations</b>	<b>12</b>
<i>Calculation of the heat output per time step (1 hour)</i>	12
<i>Calculation of incidence angle modifier <math>K_{\theta_b}(\vartheta_i)</math></i>	13
<i>Calculations of incidence angle modifier</i>	14
"Simple one directional incidence angle modifier. Case 1 above"	14
"User defined. Case 2 above"	14
<i>Calculations of solar incidence angles <math>\vartheta_i</math>, <math>\vartheta_{sunEW}</math> and <math>\vartheta_{sunNS}</math> onto a collector plane</i>	14
<i>Calculation of solar radiation onto a tilted collector plane with free orientation Tilt <math>\beta</math> and Azimuth <math>\gamma</math> including tracking surfaces.</i>	15
<i>Formulation of transformation of angles for fixed and tracking collector surfaces</i>	16
<b>C. Short explanation of input parameters and description of output data</b>	<b>17</b>
<i>Generally</i>	17
"Collector information"	17
Measurements according to: Steady State (EN 12975-2, chapter 6.1)	17
Measurements according to: Quasi Dynamic Testing (EN 12975-2, chapter 6.3)	17
"Distribution temperature"	18
"IAM Type"	18
"Simple"	18
"User defined"	18
<i>Description of the output sheet</i>	18
<b>D. Interpolation of IAM type parameters</b>	<b>20</b>
<b>E. Nomenclature</b>	<b>21</b>

## 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 unglazed 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.

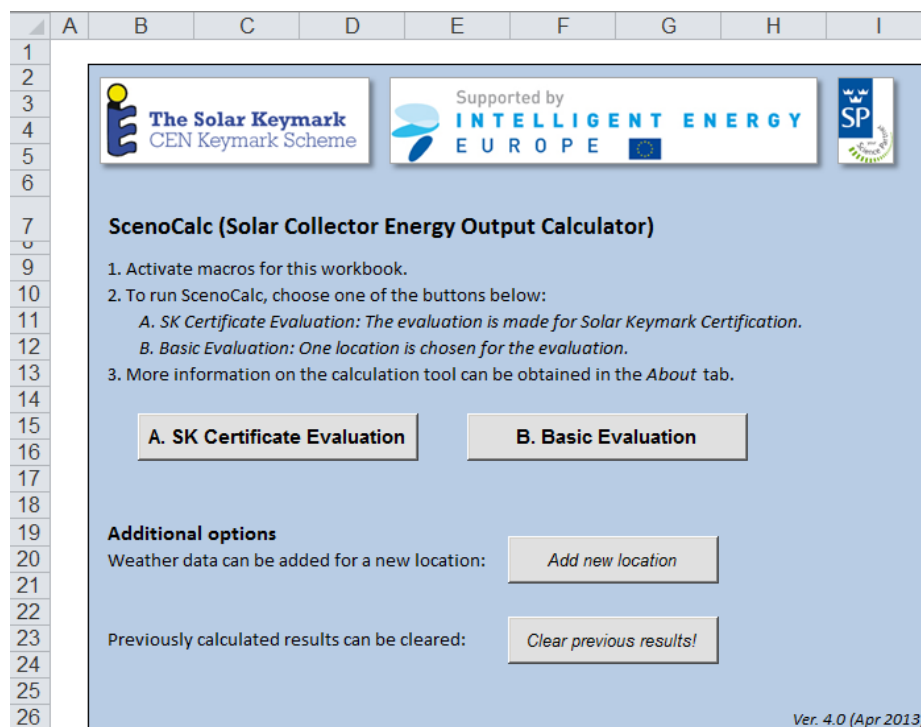


Figure 1. Main screen in ScenoCalc.

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 8. 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 (Figure 3). Location weather data is taken from a hidden sheet.

1. Fill in the data below, use the Tab key or the arrow keys for quicker data entries.  
2. Go to Page 2:

**CERTIFICATION BODY HEADER**  
field available for logo etc. Page 1/2

**Summary of EN 12975 Test Results, annex to Solar KEYMARK Certificate**

Company holding the licence	Acumpany	Country	Acumpany
Brand (optional)	Akrosol	Website	www.acumpany.de
Street, number	Arztstr. 1	E-mail	Acumpany@adomaine.de
Postal Code	80001	Tel.	+49 89 451 739
City	Munich	Fax	+49 89 234567890
Collector Type (flat plate / evacuated tubular / un-glassed air)	Evacuated tubular collector		
Integration in the roof possible? (manufacturer)	Yes		

**Annual collector output based on EN 12975 Test Annex to Solar KEYMARK Certificate**

Collector name	Location and collector temperature (T <sub>c</sub> )											
	Athens		Davos		Stockholm		Würzburg		Athens		Davos	
	25°C	50°C	75°C	25°C	50°C	75°C	25°C	50°C	75°C	25°C	50°C	75°C
Acolrizo A	2776	1922	1181	2226	1498	886	1838	978	562	1690	1074	607
Acolrizo B	5552	3844	2361	4452	2995	1771	3705	1956	1125	3381	1849	1219

**Performance test method**: Liquid heating collector - quasi-dynamic - outdoor  
**Performance parameters related**:  
 Unit: - W/(m<sup>2</sup>·K) | W/(m<sup>2</sup>·K) | W/(m<sup>2</sup>·K) | - s/m | -  
**Test results - Flow rate and fluid temp. note 2**:  
 0,700 | 3,000 | 0,015 | 0,200 | 0,000 | 0,000 | 1,000

**Bi-directional incidence**: Yes  
**Incidence angle modifiers**: Angle: 10° 20° 30° 40° 50° 60° 70° 80° 90°  
**Incidence angle modifiers**: Angle: 10° 20° 30° 40° 50° 60° 70° 80° 90°  
**Stagnation temperature**: T<sub>stagn</sub>: 176 °C  
**Effective thermal capacity**: C<sub>eff</sub>-DPA: 10 kJ/(m<sup>2</sup>·K)  
**Max. intended operating temperature**: T<sub>max,op</sub>: 100 °C  
**Max. operating pressure**: P<sub>max,op</sub>: 100 kPa

**Pressure drop table - for collector family the values shall be for the module with highest pressure drop per m<sup>2</sup> aperture**

Flow rate	0,010	0,015	0,020	0,025	0,030	0,035	0,040	0,045	0,050
Pressure drop, ΔP	11	44	100	178	278	400	544	711	900

**CERTIFICATION BODY FOOTER**  
address etc. Date of test: 2013-02-25

3. Give input data in the cells below.  
4. Start an evaluation for Solar Keymark Certification:

**CERTIFICATION BODY HEADER**  
field available for logo etc. Page 2/2

**Annual collector output based on EN 12975 Test Annex to Solar KEYMARK Certificate**

Collector name	Location and collector temperature (T <sub>c</sub> )											
	Athens		Davos		Stockholm		Würzburg		Athens		Davos	
	25°C	50°C	75°C	25°C	50°C	75°C	25°C	50°C	75°C	25°C	50°C	75°C
Acolrizo A	2776	1922	1181	2226	1498	886	1838	978	562	1690	1074	607
Acolrizo B	5552	3844	2361	4452	2995	1771	3705	1956	1125	3381	1849	1219

**Collector mounting: Fixed or tracking**:  Fixed  Tracking

**Overview of location**

Location	Latitude	East	T <sub>c</sub>	Collector orientation or tracking mode
Athens	38	1765	19,8	South, 25°
Davos	47	1716	3,2	South, 30°
Stockholm	59	1165	7,5	South, 45°
Würzburg	50	1244	9,0	South, 35°

**CERTIFICATION BODY FOOTER**  
address etc. Date of test: 2013-02-25

Figure 2. Data entry in the Solar Keymark datasheets page 1 (left) and page 2 (right) is guided by means of colour codes in the sheets. Page 2 appears after clicking the button labelled "Go to page 2".

Evaluation of annual energy output

The Solar Keymark INTELLIGENT ENERGY EUROPE SP

ScenoCalc (Solar Collector Energy Output Calculator)  
Ver. 3.23 (DRAFT, Feb 2013)

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

Identification label for the collector:

Location:

Mean fluid temperature of the collector: (0–100°C are valid)  
 °C  
 °C  
 °C

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

Figure 3. Location input.

The next step (having selected option B) is input of collector data. These are to be chosen according to the test method that has been applied to derive the model parameters (Figure 4 and Figure 5 for Quasi Dynamic or Steady State test data respectively).

The screenshot shows the 'Evaluation of annual energy output' window for ScenoCalc. The 'Evaluation method & parameters' tab is active. Under 'Choose evaluation method:', the radio button for 'Quasi Dynamic Testing (EN 12975-2, Chapter 6.3)' is selected. The parameters are as follows:

Parameter	Value	Unit / Description
etha0_b	0.70	[-] Based on aperture.
K $\theta$ ,d	1.0	[-] Diffuse angle modifier.
c1	3.00	W/m <sup>2</sup> K
c2	0.015	W/m <sup>2</sup> K <sup>2</sup>
c3	0.2	J/m <sup>2</sup> K

There is an unchecked checkbox for 'Options for unglazed collectors (not available for Steady state)'. Navigation buttons for 'Previous', 'Next', 'Cancel', and 'Run' are at the bottom.

Figure 4. Input of collector parameters based on Quasi dynamic testing.

The screenshot shows the 'Evaluation of annual energy output' window for ScenoCalc. The 'Evaluation method & parameters' tab is active. Under 'Choose evaluation method:', the radio button for 'Steady state (EN 12975-2, Chapter 6.1)' is selected. The parameters are as follows:

Parameter	Value	Unit / Description
$\eta(0)$	0.70	[-] Based on aperture.
a1	3,6	W/m <sup>2</sup> K Based on aperture.
a2	0,015	W/m <sup>2</sup> K <sup>2</sup> Based on aperture.

There is an unchecked checkbox for 'Options for unglazed collectors (not available for Steady state)'. Navigation buttons for 'Previous', 'Next', 'Cancel', and 'Run' are at the bottom.

Figure 5. Input of collector parameters based on Steady state testing.

After this the input on Incidence Angle Modifier (IAM) type and parameters are supplied (Figure 6).

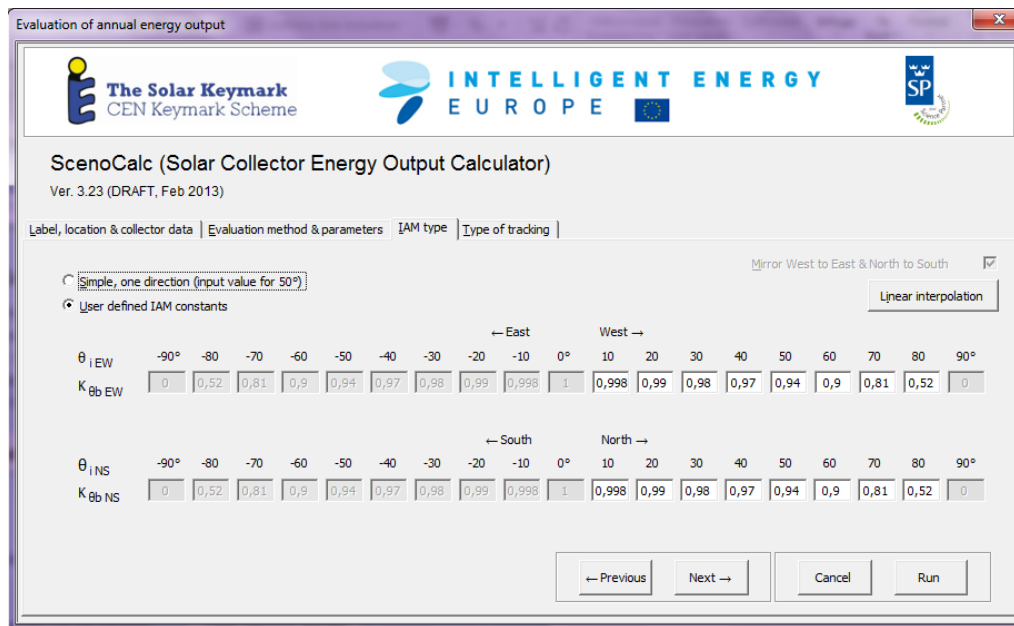


Figure 6. Input screen for IAM type and parameters (Incidence Angle Modifier).

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

When the option “Simple, one direction” is chosen, the user is prompted to input a single value at  $\theta=50$  degrees. The remaining values are then calculated from the “ $b_0$ -function”, see Eq. 4. When the option “user defined IAM constants” is selected 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. See also figure Figure 7.

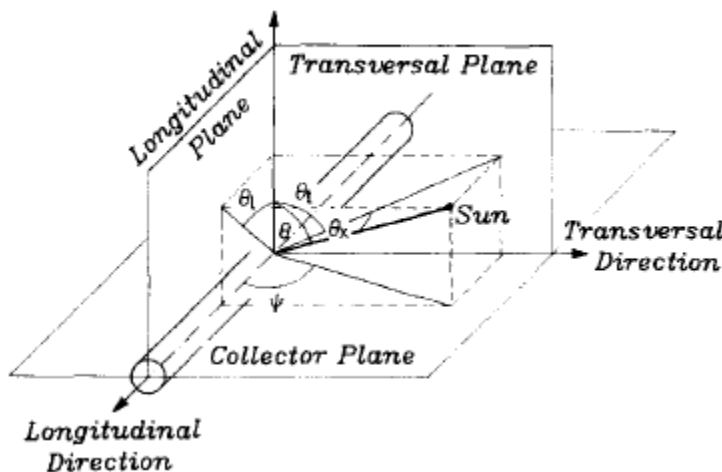


Figure 7 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

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  $K_{\theta_{b\_EW}}$ . 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  $K_{0b\_EW}$  values to the left and the higher  $K_{0b\_NS}$  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. 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 8) 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.

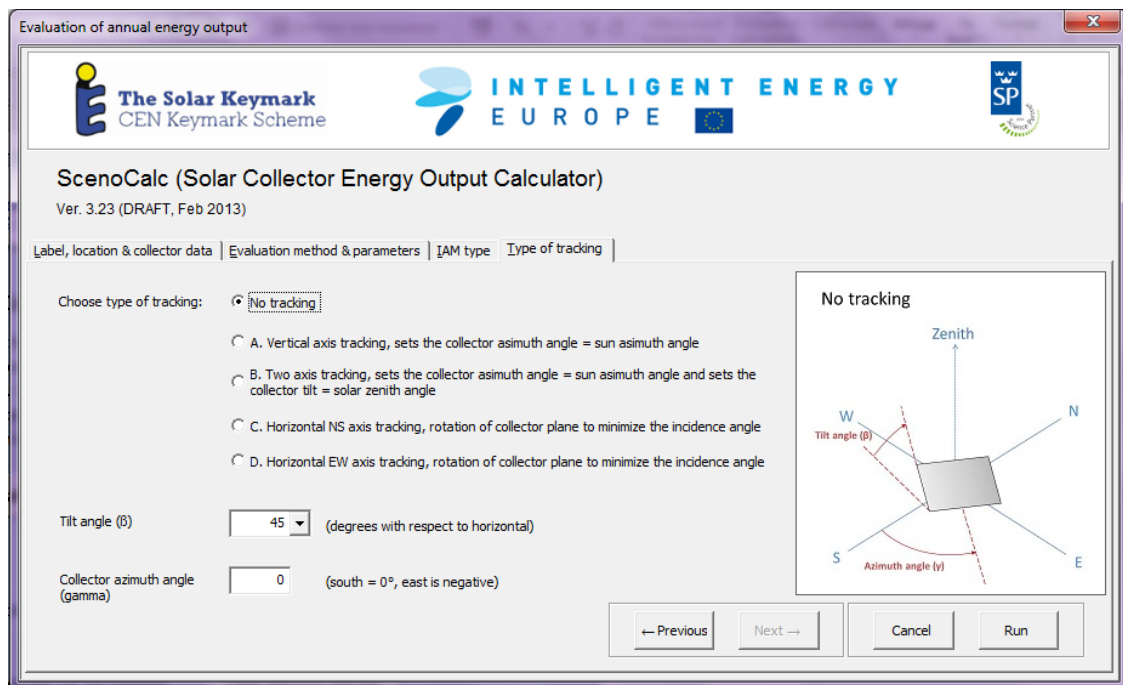


Figure 8. Type of tracking. For locations in the southern hemisphere set  $90 < \gamma < -90$ .

See also [Appendix C](#) “Short explanation of input parameters and description of output data”.

## 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 using option A (Basic evaluation)**

<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			
<b>Collector information</b> (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 9. Example of results shown in the sheet "Result".

### Appendix

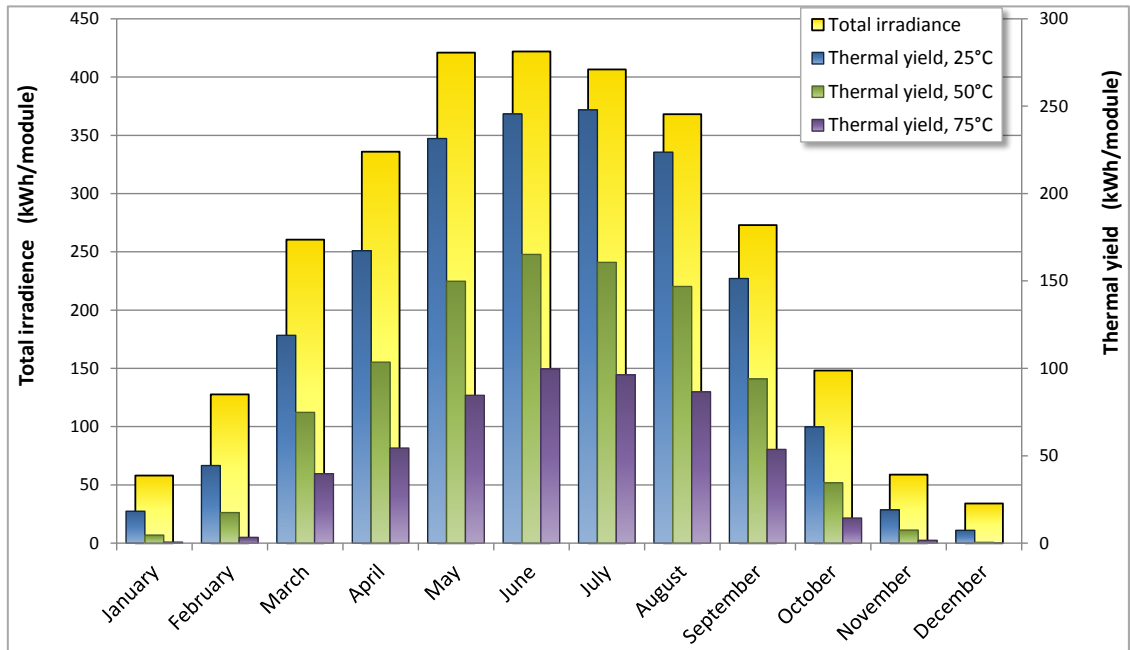


Figure 10. Example of graphical output.

## Appendix

**B. Description of the calculations****Calculation of the heat output per time step (1 hour)****The extended collector model in accordance with 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:

$$Q_t/A_a = F'(\tau\alpha)_{en} K_{0b}(\theta_L, \theta_T) G_{bT} + F'(\tau\alpha)_{en} K_{0d} G_{dT} - c_6 0.5 w_{10} G_T - c_1 (t_m - t_a) - c_2 (t_m - t_a)^2 - c_3 0.5 w_{10} (t_m - t_a) + c_4 (E_L - \sigma T_a^4) - c_5 dt_m/d\tau \quad (\text{Eq. 1})$$

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 of this term 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]
$w_{10}$ = wind speed at 10 m above ground level	[m/s]
$t_m = 0.5 \cdot (t_{in} + t_{out})$ = 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	[-]
$K_{0b}(\theta_{sunNS}, \theta_{sunEW})$ = incidence angle modifier for beam solar radiation.	[-]

$K_{0b}$  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).

$K_{0b\_EW}$  or  $K_{0b\_NS}$  are then calculated according to (Eq. 5).

$K_{0d}$ = incidence angle modifier for diffuse solar radiation (assumed to be a fixed value for each collector design). This value can be	[-]
---	-----

## Appendix

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.

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

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  $Q_{\text{module}}$ . Thus:

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

### 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.

## Appendix

**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):

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

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

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

**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

Appendix

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

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

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

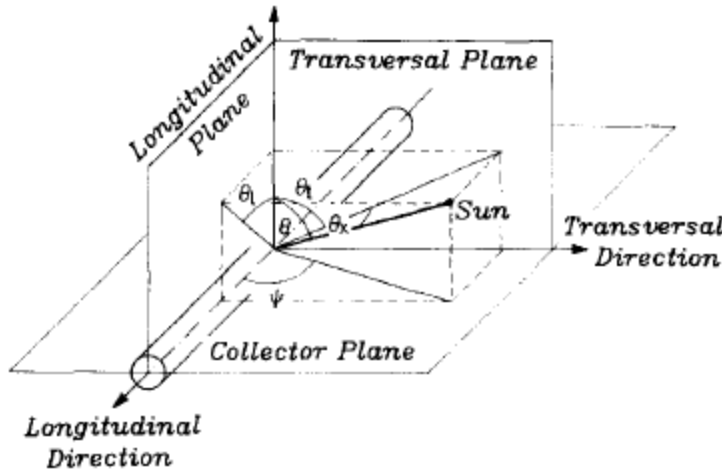


Figure 11 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

**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  $G_0$  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  $R_b = 0$

$A_i = G_{\text{b\_horis}} / G_0 =$  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

## Appendix

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 aperture area ( $A_a$ ). The calculated energy output is multiplied with the aperture area of the collector and the output per module is then presented in the output sheet.

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 the Quasi dynamic procedure 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  $K_{\theta d}$  [-]

$c_1$ , 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

## Appendix

coefficient  $c_1$  describes the first degree of temperature dependence of the heat losses from the collector in terms of  $W/m^2K$  and without wind.

*c2, Second order heat loss coefficient [ $W/m^2K^2$ ]*

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

*c3, Wind dependence of the heat loss coefficient [ $J/m^3K$ ]*

The coefficient  $c_2$  describes the wind dependence of the heat losses from the collector in terms of  $J/m^3K$ . The coefficient  $c_1$ ,  $c_3$  and the wind speed corresponds to  $a_1$  through  $a_1 = c_1 + u \cdot c_3$  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:

$$K_{0b}(\theta_i) = 1 - b_0 \cdot (1/\cos \theta_i - 1)$$

Where  $b_0$  is a coefficient to describe the IAM,  $\theta$  is the angle of incidence against the normal to the collector surface and  $K_{0b}(\theta)$  is the value to multiply with the efficiency factor at the specific angle.  $K_{0b}(50)$  is normally stated in the test report. The  $b_0$  and the remaining  $K_{0b}$  values are then calculated using 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.

### **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

## Appendix

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"	$[-]$
$K_{\theta Lcoll}$	Incidence Angle Modifier along the coll. tubes or reflectors.	$[-]$
$K_{\theta Tcoll}$	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 m2	$[\text{kWh}]$
$Q_{\text{module}}$	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	$[\text{degrees}]$
$\theta_{LsunNS}$	Solar Incidence angle in a vertical NS plane to the collector	$[\text{degrees}]$
$\theta_{TsunEW}$	Solar Incidence angle in an EW plane perpendicular to the coll.	$[\text{degrees}]$
$\theta_{Lcoll}$	Incidence angle onto coll. along the vacuum tubes or reflectors	$[\text{degrees}]$
$\theta_{Tcoll}$	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 $G_T$	
$F'(\tau\alpha)_{en}$	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]
$n = \text{Day of year}$	Day number from the beginning of the year. (Jan 1 = 1)	[ - ]