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

File name: ScenoCalc v3.10d PRELIMINARY - unlocked - incl PVT.xlsm

Introduction
This document summarises how to use Scenocalc (Solar Collector Energy Output Calculator) to evaluate annual solar collector energy 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 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 collectors, PVT collectors will be added in a future release. This document however describes the released Scenocalc plus an additional, not yet released, PVT part developed in the SCF project “Pcalc” in 2012. The different combinations of calculation modes supported in the current version of the tool are shown in the table below:

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

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.

¹ The IAM constants can be entered both symmetrically and asymmetrically (east–west and north–south) for Quasi dynamic testing, whereas only symmetrical constants are allowed for Steady state testing.
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Description of the program

The scope of the program is to evaluate the yearly energy exchange of flat plate collectors, evacuated tube collectors, concentrating collectors and unglazed collectors.

Information flow

The user of ScenoCalc starts by pressing the button “Start evaluation” in Figure 1.

![Solar Energy Output Calculator (SEnOCalc)](image)

In the pop-up window that appears, the user is asked to input data from solar collector testing (see Figure 2). When data has been entered, the monthly amount of heat and optionally electricity that could be extracted from the solar collector is calculated. The results are presented in a table and 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. All hidden sheets can be unhidden without needing a password.

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 the locations Athens, Davos, Stockholm and Wurzburg and to temperatures ranging from 0°C to 100°C (Figure 2). Location weather data is taken from a hidden sheet. Optionally, the user can choose PVT collectors and this choice opens up further input fields e.g. the absorber area.
Figure 2. Location, temperature and reference area(s) input. Optional choice of PVT.

The next step is input of collector data. The former is 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).

Figure 3. Input of PVT collector thermal parameters based on Quasi dynamic testing and PV parameters based on peak power measurements.
Figure 4. Input of PVT collector thermal parameters based on Steady state testing and PV parameters based on peak power measurements. **Option for unglazed collectors is NOT available yet.**

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

**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 \( K_{\theta, \text{coll}} \) and \( K_{\theta, \text{Tcoll}} \) on the input rows above for \( K_{\theta, \text{EW}} \) and \( K_{\theta, \text{NS}} \) according to how the collector is mounted when it’s in operation. Related to the collector design \( \theta_{\text{coll}} \) and \( \theta_{\text{Tcoll}} \) directions and angles are defined as \( \theta_{\text{Tcoll}} = \) Incidence angle projected on a plane perpendicular to the collector optical axis and \( \theta_{\text{coll}} = \) Incidence angle projected on a plane parallel to the collector optical axis. \( K_{\theta, \text{coll}} \) and \( K_{\theta, \text{Tcoll}} \) should follow the collector rotation if the vacuum tubes or reflectors are mounted horizontally or vertically. See also figure 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 $K_{\theta_L\text{Coll}}$ values input as $K_{\theta_L\text{EW}}$ and $K_{\theta_T\text{Coll}}$ input as $K_{\theta_L\text{NS}}$. “Vertical” vacuum tubes directed NS will have its $K_{\theta_L\text{Coll}}$ values input as $K_{\theta_L\text{NS}}$ and $K_{\theta_T\text{Coll}}$ input as $K_{\theta_L\text{EW}}$. 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 $K_{\theta_L\text{EW}}$ values to the left and the higher $K_{\theta_L\text{NS}}$ 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 $K_{\theta_L\text{Coll}}$ and $K_{\theta_T\text{Coll}}$ and $\theta_{L\text{Coll}}$ and $\theta_{T\text{Coll}}$ well defined and checked to avoid mistakes when using the values. An “Interpolate” 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.

Finally the type of tracking 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.
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 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
   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


[7] Personal communication and unpublished SOLNET material Michel Haller SPF


A. Example from the output sheet

Results from the Solar Energy Output Calculator (SEnOCalc)  
Version 3.10d (PRELIMINARY, Not recommended for use, April 2012)

Identification label for the solar collector: Not specified  
Date of evaluation: 2 September, 2012  
Evaluation method: Steady state

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

<table>
<thead>
<tr>
<th>Total irradiance</th>
<th>Yield for three collector mean temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25°C</td>
</tr>
<tr>
<td>January</td>
<td>66</td>
</tr>
<tr>
<td>February</td>
<td>137</td>
</tr>
<tr>
<td>March</td>
<td>264</td>
</tr>
<tr>
<td>April</td>
<td>344</td>
</tr>
<tr>
<td>May</td>
<td>471</td>
</tr>
<tr>
<td>June</td>
<td>499</td>
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<tr>
<td>July</td>
<td>471</td>
</tr>
<tr>
<td>August</td>
<td>389</td>
</tr>
<tr>
<td>September</td>
<td>275</td>
</tr>
<tr>
<td>October</td>
<td>152</td>
</tr>
<tr>
<td>November</td>
<td>63</td>
</tr>
<tr>
<td>December</td>
<td>39</td>
</tr>
<tr>
<td><strong>Year</strong></td>
<td><strong>3 170</strong></td>
</tr>
</tbody>
</table>

**PV output per collector module (kWh/module)**

<table>
<thead>
<tr>
<th>Total irradiance</th>
<th>Yield for three collector mean temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>October</td>
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</tr>
<tr>
<td>November</td>
<td>63</td>
</tr>
<tr>
<td>December</td>
<td>39</td>
</tr>
<tr>
<td><strong>Year</strong></td>
<td><strong>3 170</strong></td>
</tr>
</tbody>
</table>
Appendix

Location: Stockholm
Longitude: -18.08 (positive longitude = west of the prime meridian)
Latitude: 59.35
Time period for climate data: 1996-2005

**Collector parameters** (based on the aperture area)
Aperture area $2.5 \text{ m}^2$
$\eta_0$ 0.700
$F'(\alpha)_\text{en}$ 0.710
$K_{0,d}$ 0.908
$a_1$ 3.6 W/m²/K
$a_2$ 0.015 W/m²/K²

**PV parameters** (based on the aperture area)
Absorber area $2.3 \text{ m}^2$
$P_{\text{max PV}}$ 100 W
$P_{\text{PV temp dep}}$ 0.004 1/°C
$C_{\text{bond}}$ 150 W/m²/K
$PR_{\text{sys}}$ 0.8 (System performance ratio)

Type of tracking: Horisontal EW axis tracking
Tilt angle: Solar adapting tilt angle
Azimuth angle: Step-wise varying: 0° for $|\text{sun azimuth}| < 90°$, and 180° for $|\text{sun azimuth}| \geq 90°$

IAM Type: Simple, one-direction

*Figure 8. Example of results for a PVT collector shown in the sheet “Result”.*
Appendix

Figure 9. Example of graphical output for the thermal part of a PVT.

Figure 10. Example of graphical output for the PV part of a PVT.
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 m² of collector:

\[
\frac{Q_t}{A_a} = F'(\alpha)_{en} K_{ib}(\theta_{in}, \theta_{t}) G_{BT} + F'(\alpha)_{en} K_{ib} G_{DT} - c_6 0.5 w_{10} G_T - c_1 (t_m - t_a) - c_2 (t_m - t_a)^2 - c_3 0.5 w_{10} (t_m - t_a) + c_4 (E_L - \sigma T_a^4) - c_5 \frac{dt_m}{d\tau}
\]  

(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/m²]
- \( G_{DT} \): diffuse solar radiation in the collector plane [W/m²]
- \( G_T \): total (beam + diffuse) solar radiation in the collector plane [W/m²]
- \( \theta_{sunNS}, \theta_{sunEW} \): 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]
- \( t_m = 0.5(t_{in} + t_{out}) \): 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/m²]
- \( T_a \): ambient temperature close to the collector (in the shade) [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:

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

\( K_{ib} \) 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). \( K_{ib,EW} \) or \( K_{ib,NS} \) are then calculated according to (Eq. 5).

\( K_{id} \): incidence angle modifier for diffuse solar radiation [-]

(assumed to be a fixed value for each collector design). This value can be
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 \( a_1 \) \[ W/(m^2 K) \]

\( c_2 = \) temperature dependence in the heat loss coefficient equal to \( a_2 \) \[ W/(m^2 K^2) \]

\( c_3 = \) wind speed dependence of the heat losses equal to \( F'U_{\text{wind}} \) \[ J/(m^3 K) \]

\( c_4 = \) long wave dependence of the heat losses, equal to \( F'\varepsilon \) \[-\]

\( c_5 = \) effective thermal capacitance, equal to \( (mC)_e \) \[ J/(m^2 K) \]

\( c_6 = \) 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 \( F'(\tau\alpha)_{\text{en}} \) 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 \( Q/A \) are not meaningful and therefore set to 0 in each particular time step.

The annual energy gain per \( m^2 \) of collector at the preset temperature \( t_m \) is equal to the sum of the mean heat output of all time steps.

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

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

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

**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 \( \text{(i.e. where the incidence angle modifier vary differently in the direction of east and west or north and south).} \) 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 then 90, \( K_{\theta b}(\theta_i) \) 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 \( |\theta_i| > 90 \text{ degrees} \) can be used to determine if the sun is behind the collector plane and \( K_{\theta b}(\theta_i) \) should be set to 0.
Calculations of incidence angle modifier

"Simple one directional incidence angle modifier. Case 1 above"

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

"User defined. Case 2 above"

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

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

$$K_{th,i} = K_{th,EW} \text{ or } K_{th,NS}$$

$$K_{th}(\theta_i) = K_{th,EW} \cdot K_{th,NS} \quad \text{ (Eq. 6)}$$

---------------Start of PVT model description-----------------------------

**Model for the Electrical part of a PVT module with MPP tracker active**

The PV modeling here is assuming that the PV part of the PVT collector is connected to a suitable MPP (Maximum Power Point) tracker, so that the PV module is operating close to the maximum on the electrical I-V curve all the time, during test and also for calculation of annual performance.

It is also assumed that the load is larger than the collector PV production all the time, so that all PV output can be utilized. The DC output is calculated first. Then a fixed performance ratio PR is proposed to estimate also the net AC output to the grid in a standardized way.

The deeper PV and PVT theory is much more complex, but this a reasonable level of accuracy based on PVT work since the 1970:ies and presented in IEA SH&C Task 35 work. This theory is a bit ahead of the PVT test procedure standardization. Therefore some parameters in the proposed PV model have to be chosen from experience, if not available from a test of the PVT module.

**PVT cell temperature estimation for temperature correction needs**

- $T_m$: Collector mean fluid temperature (°C), $(T_{out} + T_{in}) \cdot 0.5$
- $T_{cell}$: PV cell temperature (°C, deviation from PV cell test performance at 25°C changes performance)
- $Q$: Collector thermal output (W) for the whole module area with MPP tracking in operation (see above)
- $A_d$: Collector module reference area (m²), typically the aperture area.
- $A_{abs}$: Collector absorber area (almost the same as $A_d$ for flat plate PVT collectors, but much smaller for concentrating PVT collectors)
- $A_{cell}$: Photovoltaic cell area (m²), total for the module.
- $P_{T,dep}$: Temperature dependence of electric power output (for silicon cells typ. 0.4%/°C = 0.004°C⁻¹)
- $C_{bond}$: Conductance from the PV cell to the fluid in the absorber. $C_{bond}$ influence the PV cell over temperature above $T_m$ in the collector. ($C_{bond}$ is typically 100-2000 W/m²/K for a well-designed PVT. It can be estimated from $C_{bond} = \lambda / d = \lambda$ cell lamination material / thickness of lamination.

Example: Flat plate PVT with EVA encapsulation: 0.15 W/m/K / 0.001 m = 150 W/m²/K.
Example: Concentrating PVT using special thermal tape 0.8 W/m/K / 0.0005 m = 1600 W/m²/K

Correction for temp drop in absorber. This relation is inserted in Eq. PVT-2 below
T_{cell} = T_m + Q/ A_{abs} / C_{bond}  

Eq. PVT-1

PVT cell temperature correction for power output:
Cell_{Tcorr} = (1 - PV_{Temp,dep}( T_m + Q/ A_{abs} / C_{bond} - 25)) 

Eq. PVT-2

PVT electrical power output:

Parameters in PV power output model:
\eta_{cell} = PV module efficiency at 25C cell temperature, normal incidence to the collector 1000 W/m² solar radiation and with MPPT in operation (typical value \eta_{cell} = 10-20% = 0.10 - 0.20)

\eta_{cell} can be calculated as:
\eta_{cell} = P_{max_PV} / (A_a * 1000 )  1000 comes from the 1000W/m2 at standard test conditions.  Eq. PVT-3

P_{max_PV} = Maximum PV output for solar radiation intensity of 1000 W/m2 and cell temperature 25C. This needs to be further defined how to find this from a PVT test with a mix of beam and diffuse radiation and a cell temperature above 25C. Proposal for test evaluation: In principle a method similar to the QDT applying MLR on Eq. PVT-5 is possible, but needs validation with measured data. An intermediate step could be to solve Eq. PVT-5 for P_{max_PV} and use data for near normal incidence and low diffuse fraction like a stationary test point to estimate P_{max_PV}.

P_{max_PV} = 1000 * Q_{pv_DC} / [(1 - PV_{Temp,dep}( T_m + Q/ A_{abs} / C_{bond} - 25)) * (G_{bT} K_{0b(\theta)_{PV}} + G_{dT} K_{0d_{PV}}) ]

Eq. PVT-5

IAM incidence angle modifier dependence for PVT
Beam IAM for collectors with simple b_0 IAM dependence
b_{b0pv} = b_{0,thermal} if no separate PV b_0 test data is available.

K_{0b(\theta)_{PV}} = max(0 ; (1 - b_{b0pv} * (1 / \cos(\theta) - 1))) if the b_0 function is used for IAM.

Beam IAM in the general case for collectors with more complex IAM:
K_{0b(\theta)_{PV}} = K_{0b(\theta)_{thermal}} if no separate PV beam IAM dependence is available. Can also be angle by angle IAM, if determined in a thermal or PV test.

Diffuse IAM
K_{0d_{PV}} = K_{0d,thermal} if no separate PV diffuse IAM test value is available

Variables used in the PV model available already from thermal part of the Excel tool:
\theta_i = Incidence angle for beam solar radiation onto the collector
G_{bT} = Total solar radiation in tilted PVT collector plane
G_{dT} = Diffuse solar radiation
T_m = Average fluid temperature in the collector (from input data)

DC power output for the module:
Q_{pv,DC} = \eta_{cell} * Cell_{Tcorr} * (G_{bT} * K_{0b(\theta)_{PV}} + G_{dT} * K_{0d_{PV}}) * A_a  

Eq. PVT-4

If the equations for \eta_{cell} and Cell_{Tcorr} are inserted in the equation above the total DC Power output is:

Q_{pv,DC} = P_{max_PV} /1000 * (1 - PV_{Temp,dep}( T_m + Q/ A_{abs} / C_{bond} - 25)) * (G_{bT} K_{0b(\theta)_{PV}} + G_{dT} K_{0d_{PV}})  

Eq. PVT-5
Appendix

Note that the reference area is cancelled by using $P_{max_{PV}}$ instead of efficiency. The absorber area for the module is still needed though to estimate the temperature rise of the cells above $T_m$

Ac power output for the module:

$P_{sys} = \text{System Performance ratio, taking into account inverter efficiency and other system losses for example mismatch between modules and cable losses. This is here proposed to be simplified to an average value for the whole year and not hour by hour dependent and not inverter model dependent as then you also have to decide a specific system. A typical value for a well-designed grid connected PV system is }$ $P_{sys} = 0.8$

$Q_{pv,AC} = Q_{pv,DC} \times P_{sys}$  

Eq. PVT-6

-------------------------End of PVT description---------------------------------------------

Calculations of solar incidence angles $\theta_i$, $\theta_{sunEW}$ and $\theta_{sunNS}$ 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).

$\text{Solar time} = (\text{hour}_\text{day} - 0.5) \cdot 3600 + E \cdot 60 + 4 \cdot (\text{STD}_\text{longitude} - \text{longitude}) / 3600 \text{ ref [5] [hours]}$  

(Eq. 7)

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

(Eq. 8)

$B = (\text{day}_\text{of}_\text{year} - 1) \cdot 360 / 365 \text{ ref [5]}$  

(Eq. 9)

$\delta = 23.45 \cdot \sin(360 \cdot (284 + \text{day}_\text{of}_\text{year}) / 365) \text{ ref [5]}$  

(Eq. 10)

Hour angle

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

(Eq. 11)

Solar Zenith angle

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

(Eq. 12)

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

$\gamma_s = \text{SIGN}(\omega) \cdot \left\lfloor \arccos\left(\left(\cos \theta_Z \sin \phi - \sin \delta\right) / (\sin \theta_Z \cos \phi)\right) \right\rceil \text{ ref [5]}$  

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

(Eq. 13)

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

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

$\text{(}>0 \text{ means to the “west” of collector normal)}$  

Else

$\theta_{sunEW} = 90$  

(Eq. 14)

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

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

$\text{(}>0 \text{ means to the “north” of collector normal)}$  

Else

$\theta_{sunNS} = 90$  

(Eq. 15)
Incidence angle between the direction of the sun and collector normal for all orientations of the collector, with tilt $\beta$ and azimuth $\gamma$

$$\theta_i = \arccos[\cos \theta_Z \cdot \cos \beta + \sin \theta_Z \cdot \sin \beta \cdot \cos (\gamma_s - \gamma_s)] \quad \text{ref [5]}$$  \hspace{1cm} \text{(Eq. 16)}

![Diagram](image_url)

*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 $G_{\text{horis}}$, $G_{b_{\text{horis}}}$, and $G_{d_{\text{horis}}}$ are used for total, beam and diffuse solar radiation onto a horizontal surface. $G_{bn}$ 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:

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

$$G_{bT} = G_{b_{\text{horis}}} R_b \quad \text{and} \quad G_{dT} = G_T - G_{bT}$$

*Note that $G_{bT}$ 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 $R_b=0$

$A_i = G_{b_{\text{horis}}}/G_o$ = 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

$G_o = 1367 \cdot (1+0.033 \cdot \cos(360\cdot n/365) \cdot \cos(\theta_2))$

If $G_{\text{horis}}$ and $G_{bn}$ are given in the climate file $G_{b_{\text{horis}}} = G_{bn} \cdot \cos(\theta_2)$ and $G_{d_{\text{horis}}} = G_{\text{horis}} - G_{b_{\text{horis}}}$ (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*
Appendix

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 $\beta = \theta_2 + 0.001$ 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 $\beta = \arctan(\tan(\theta_2) | \cos(\gamma - \gamma_s)|)$ 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 $\beta = \arctan(\tan(\theta_2) | \cos(\gamma_s)|)$ and collector azimuth $\gamma = 0$ if $|\gamma_s| < 90$ and $\gamma = 180$ if $|\gamma_s| \geq 90$
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$^2$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 $a_1$ describes the first degree of temperature dependence of the heat losses from the collector in terms of W/m$^2$K and with a wind speed at 2-4 m/s.

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

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.

$F'(\tau_0)_{en}$, Collector optical efficiency for direct irradiance [-]
The parameter $F'(\tau_0)_{en}$ 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 \([W/m^2\,K]\)**
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 \(W/m^2\,K\) and without wind.

**c2. Second order heat loss coefficient \([W/m^2\,K^2]\)**
The coefficient \(c_2\) describes the second degree of temperature dependence of the heat losses from the collector in terms of \(W/m^2\,K^2\).Corresponds to a \(a_2\) in the Steady State measurements.

**c3. Wind dependence of the heat loss coefficient \([J/m^3\,K]\)**
The coefficient \(c_3\) describes the wind dependence of the heat losses from the collector in terms of \(J/m^3\,K\). The coefficient \(c_1\), \(c_3\) and the wind speed corresponds to \(a_3\) = \(c_1 + u\cdot c_3\) 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 \(F\cdot e\) \(-\)**

**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:

\[
K_{\theta_b}(\theta_i) = 1 - b_0 \cdot (1/\cos \theta_i - 1)
\]

Where \(b_0\) is a coefficient to describe the IAM, \(\theta\) is the angle against the collector surface and \(K_{\theta_b}(\theta)\) 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. \(K_{\theta_b}(50)\). 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.
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 $F'(\tau\alpha)_{\text{en}}$ och $K_{\text{sd}}$ are showed if the SS alternative is used.
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°, 0° and 90°. 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.
### E. Nomenclature

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>First degree of temperature dependence (Steady State)</td>
<td>[Wm$^{-2}$K$^{-1}$]</td>
</tr>
<tr>
<td>$a_2$</td>
<td>Second degree of temperature dependence (Steady State)</td>
<td>[Wm$^{-2}$K$^{-2}$]</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Aperture area of the collector</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$A_G$</td>
<td>Gross area of the collector</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$b_n$</td>
<td>Constant for calculations of the incidence angle modifier</td>
<td>[-]</td>
</tr>
<tr>
<td>$c_1$</td>
<td>First degree of temperature dependence (Dynamic testing)</td>
<td>[Wm$^{-2}$K$^{-1}$]</td>
</tr>
<tr>
<td>$c_2$</td>
<td>Second degree of temperature dependence (Dynamic testing)</td>
<td>[Wm$^{-2}$K$^{-2}$]</td>
</tr>
<tr>
<td>$c_d$</td>
<td>Wind dependent of the heat loss coefficient (Dynamic testing)</td>
<td>[J/m$^2$K]</td>
</tr>
<tr>
<td>$c_e$</td>
<td>Effective thermal capacitance of the heat losses, equal to $F'$</td>
<td>[J/(m$^2$ K)]</td>
</tr>
<tr>
<td>$c_6$</td>
<td>Wind dependence of the collector zero loss efficiency</td>
<td>[s/m]</td>
</tr>
<tr>
<td>$F'$</td>
<td>Collector efficiency factor</td>
<td>[-]</td>
</tr>
<tr>
<td>$G^*$ or $G_T$</td>
<td>Global or Total irradiance in collector plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_{hor}$</td>
<td>Global or Total irradiance in horizontal plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_{0, hor}$</td>
<td>Beam irradiance in horizontal plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_{diff, hor}$</td>
<td>Diffuse irradiance in horizontal plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_{b}$</td>
<td>Beam irradiance in normal direction to the sun</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_o$</td>
<td>Extraterrestrial Radiation on horizontal plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_{WT}$</td>
<td>Beam irradiance in Tilted collector plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$G_{IT}$</td>
<td>Diffuse irradiance in Tilted collector plane</td>
<td>[Wm$^{-2}$]</td>
</tr>
<tr>
<td>$LT$</td>
<td>Local time</td>
<td>[h]</td>
</tr>
<tr>
<td>$K_{00}(\theta_i)$</td>
<td>Incidence angle modifier for direct irradiance</td>
<td>[-]</td>
</tr>
<tr>
<td>$K_{ih, EW}$</td>
<td>Incidence Angle Modifier (IAM) “EW” or “horizontally”</td>
<td>[-]</td>
</tr>
<tr>
<td>$K_{ih, NS}$</td>
<td>Incidence Angle Modifier (IAM) “NS” or “vertically”</td>
<td>[-]</td>
</tr>
<tr>
<td>$K_{l, coll}$</td>
<td>Incidence Angle Modifier along the coll. tubes or reflectors.</td>
<td>[-]</td>
</tr>
<tr>
<td>$K_{l, Tcoll}$</td>
<td>Incidence Angle Modifier perpend. to coll. tubes or reflectors.</td>
<td>[-]</td>
</tr>
<tr>
<td>$K_d$</td>
<td>Incidence angle modifier for diffuse irradiance</td>
<td>[-]</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>Mean power output during one time step</td>
<td>[W]</td>
</tr>
<tr>
<td>$Q/A_0$</td>
<td>Useful energy extracted from the collector per m$^2$</td>
<td>[kWh]</td>
</tr>
<tr>
<td>$Q_{module}$</td>
<td>Useful energy extracted from the collector, annual energy gain</td>
<td>[kWh per module]</td>
</tr>
<tr>
<td>$t$</td>
<td>time step</td>
<td>[h]</td>
</tr>
<tr>
<td>$t_a$</td>
<td>Ambient air temperature</td>
<td>[$^\circ$C]</td>
</tr>
<tr>
<td>$t_m$</td>
<td>Collector mean temperature</td>
<td>[$^\circ$C]</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>Solar Zenith angle ($=90\cdot\theta_n$)</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Solar Azimuth angle (0 = south, east negative)</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Tilt angle of collector plane from horizontal</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Collector azimuth angle from south =0, east negative</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Solar Declination</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Solar hour angle</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Angle of incidence onto collector. (from collector normal)</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Latitude of collector and climate data location</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\theta_{l, sun, NS}$</td>
<td>Solar Incidence angle in a vertical NS plane to the collector</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\theta_{l, sun, EW}$</td>
<td>Solar Incidence angle in an EW plane perpendicular to the coll.</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\theta_{l, coll}$</td>
<td>Incidence angle onto coll. along the vacuum tubes or reflectors</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\theta_{T, coll}$</td>
<td>Incid. angle onto coll. perpendicular to vac. tubes or reflectors</td>
<td>[degrees]</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>Solar collector zero-loss efficiency at ($t_m - t_a$) = 0</td>
<td>[-]</td>
</tr>
<tr>
<td>$F'(\pi\alpha)_{en}$</td>
<td>Effective transmittance-absorptance product at ($t_m - t_a$) = 0</td>
<td>[-]</td>
</tr>
</tbody>
</table>
Appendix

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

$T$ Transversally to directions of vacuum tubes or reflectors

$L$ Longitudinally along vacuum tubes and reflectors

<table>
<thead>
<tr>
<th>Hour_day</th>
<th>Time stamp in the Excel code during the day (first hour = 1.0) [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{loc}$</td>
<td>Longitude of location (e.g. Stockholm -18.080) [degrees]</td>
</tr>
<tr>
<td>$L_{std}$</td>
<td>Longitude of time zone (e.g. Sweden -15.0) [degrees]</td>
</tr>
<tr>
<td>$E$</td>
<td>Equation of time correcting for the eccentric path of the earth around the sun. [minutes]</td>
</tr>
<tr>
<td>$B$</td>
<td>“Earth position” around the sun during the year 0-360 deg. [degrees]</td>
</tr>
</tbody>
</table>

n = Day of year Daynumber from the beginning of the year. (Jan 1 = 1) [ - ]