

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:

	Steady state testing	Quasi dynamic testing
Unglazed collectors	✗	✓
One-directional IAM type	✓	✓
User-defined IAM type	✓	✓
Asymmetric IAM constants (E-W and N-S) ¹	✗	✓
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.

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.

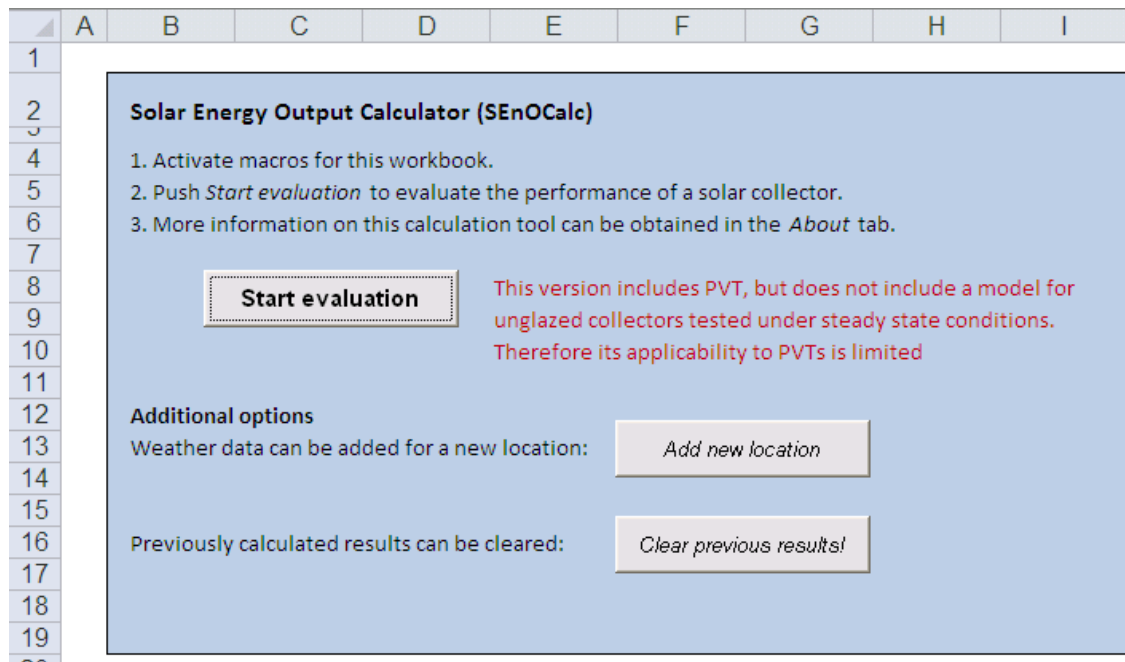


Figure 1. Main screen in ScenoCalc.

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.

SEncalc (Solar Energy Output Calculator)
Version 3.10d (PRELIMINARY, Not recommended for use, April 2012)

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

Identification label for the collector:

Location:

Choose type of collector:
 Solar thermal collector (heat only)
 PVT collector (both electricity and heat)

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

Aperture area: m²
 Absorber area: m²

Next → | Cancel | Run

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).

SEncalc (Solar Energy Output Calculator)
Version 3.10d (PRELIMINARY, Not recommended for use, April 2012)

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

Choose evaluation method:
 Steady state (EN 12975-2, Chapter 6.1)
 Quasi Dynamic Testing (EN 12975-2, Chapter 6.3)

PV parameters
 Pmax PV: W
 PVtemp dep: 1/°C
 cbond: W/m²/K
 PRsys: [-] System performance ratio

Options for unglazed collectors (not available for Steady state)

F'(τ,α)en: [-] Based on aperture.
 kB,d: [-] Diffuse angle modifier.
 c1: W/m²K
 c2: W/m²K²
 c3: J/m²K

a1 = c1 + 3*c3: W/m²K Based on aperture; including wind 3 m/s.
 a2 = c2: W/m²K² Based on aperture.

← Previous | Next → | Cancel | Run

Figure 3. Input of PVT collector thermal parameters based on Quasi dynamic testing and PV parameters based on peak power measurements.

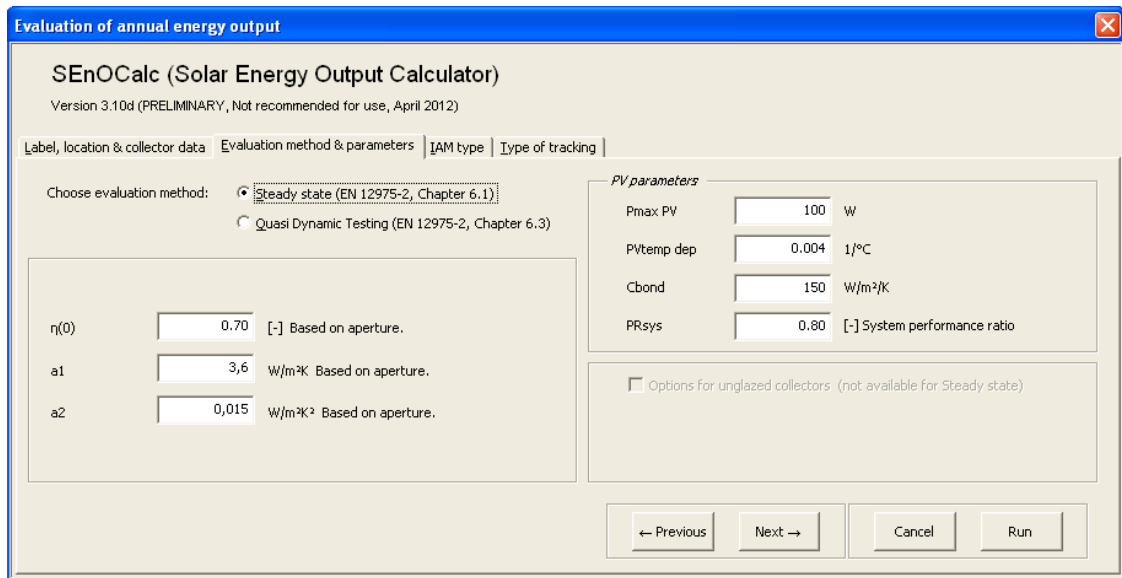


Figure 4. Input of PVT collector thermal parameters based on Steady state testing and PV parameters based on peak power measurements. Option for unglazed collectors is NOT available yet.

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

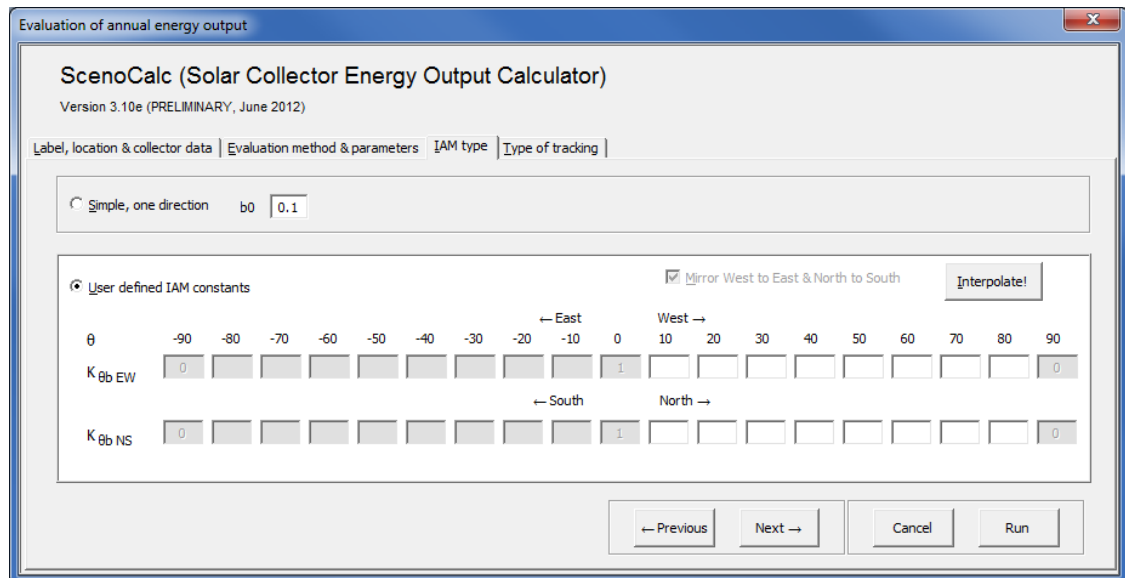


Figure 5. Information on IAM type (Incidence Angle Modifier).

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

The user makes the input of $K_{\theta_{Lcoll}}$ and $K_{\theta_{Tcoll}}$ on the input rows above for $K_{\theta_{b_EW}}$ and $K_{\theta_{b_NS}}$ according to how the collector is mounted when it's in operation. Related to the collector design θ_{Lcoll} and θ_{Tcoll} directions and angles are defined as θ_{Tcoll} =Incidence angle projected on a plane perpendicular to the collector optical axis and θ_{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 6.

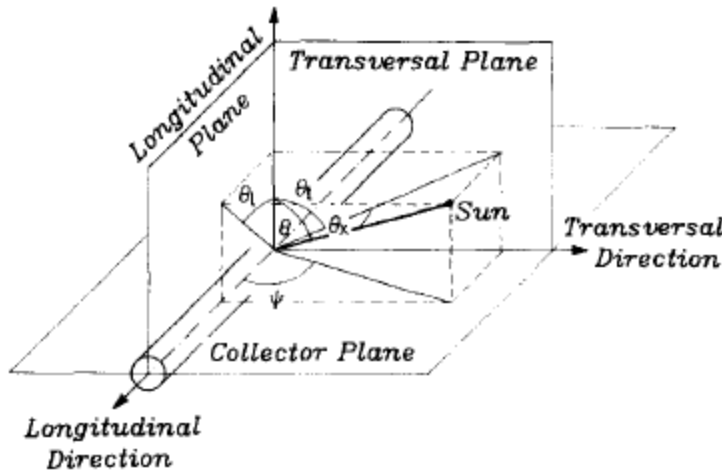


Figure 6 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

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 $K_{\theta_{b_EW}}$. A collector with an asymmetrical IAM which performs better in the morning and in winter time than in the afternoon and in summer should thus have the higher $K_{\theta_{b_EW}}$ values to the left and the higher $K_{\theta_{b_NS}}$ values to the left.

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

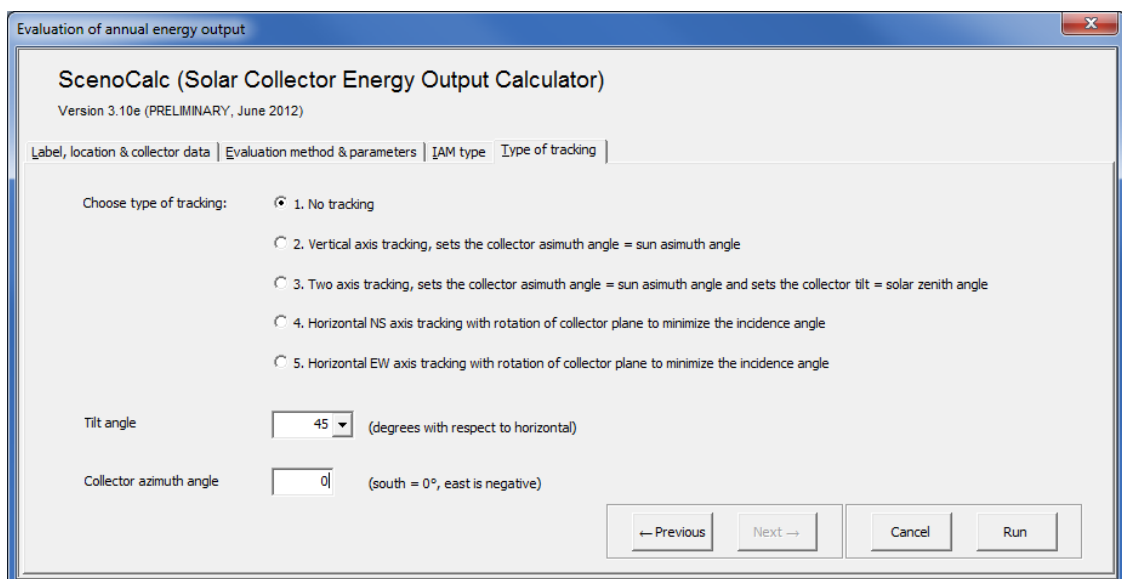


Figure 7. Type of tracking.

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

- [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
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- [5] Duffie, J.A. and Beckman W.A. *Solar Engineering of Thermal Processes* (2006)
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- [7] Personal communication and unpublished SOLNET material Michel Haller SPF
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- [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**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)

	Total irradiance	Yield for three collector mean temperatures		
		25°C	50°C	75°C
January	66	25	10	2
February	137	53	25	7
March	264	123	80	44
April	344	169	104	55
May	471	259	159	88
June	499	293	188	108
July	471	289	182	103
August	389	235	149	87
September	275	153	97	57
October	152	72	40	19
November	63	25	12	4
December	39	11	3	0
Year	3 170	1 708	1 048	573

PV output per collector module (kWh/module)

	Total irradiance	Yield for three collector mean temperatures		
		25°C	50°C	75°C
January	66	2,0	1,8	1,6
February	137	4,2	3,8	3,4
March	264	7,9	7,1	6,4
April	344	10,2	9,2	8,2
May	471	13,9	12,6	11,2
June	499	14,8	13,3	11,9
July	471	13,9	12,6	11,2
August	389	11,5	10,4	9,2
September	275	8,2	7,4	6,6
October	152	4,6	4,1	3,7
November	63	1,9	1,7	1,5
December	39	1,2	1,1	1,0
Year	3 170	94,3	85,1	75,8

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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 m²
 η_0 0,700
 $F'(\tau \alpha)_{en}$ 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 m²
 $P_{max PV}$ 100 W
 $PV_{temp dep}$ 0,004 1/°C
 C_{bond} 150 W/m²/K
 PR_{sys} 0,8 (*System performance ratio*)

Type of tracking: Horizontal EW axis tracking

Tilt angle: Solar adapting tilt angle

Azimuth angle: Step-wise varying: 0° for |sun azimuth| < 90°, and 180° for |sun azimuth| >= 90°

IAM Type: Simple, one-direction

Figure 8. Example of results for a PVT collector shown in the sheet "Result".

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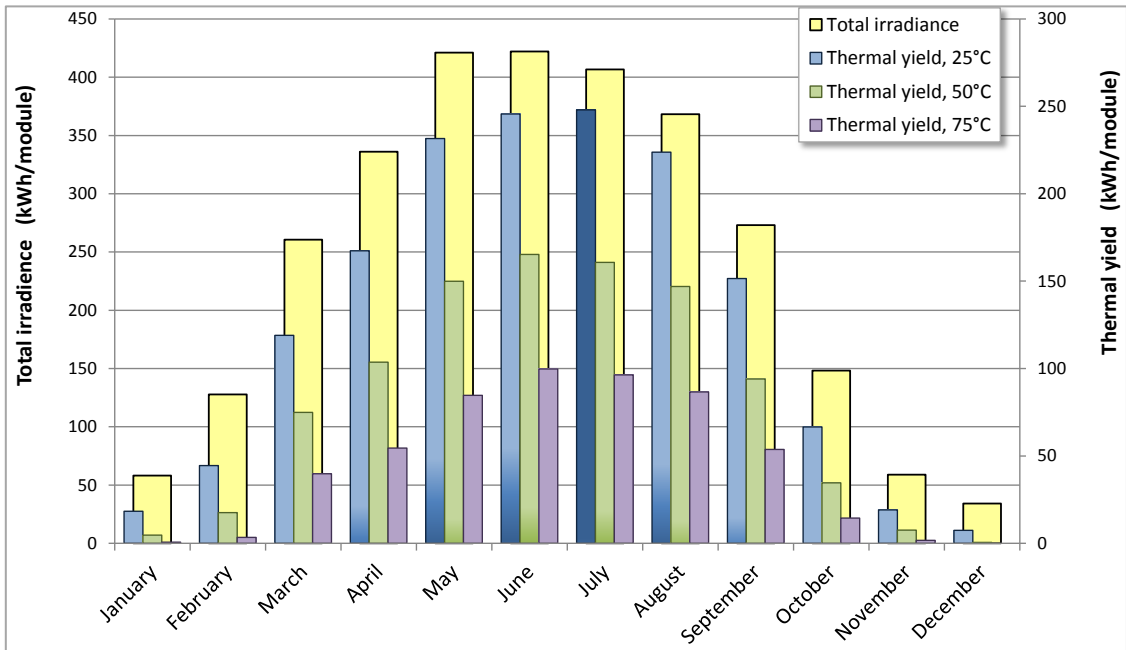


Figure 9. Example of graphical output for the thermal part of a PVT.

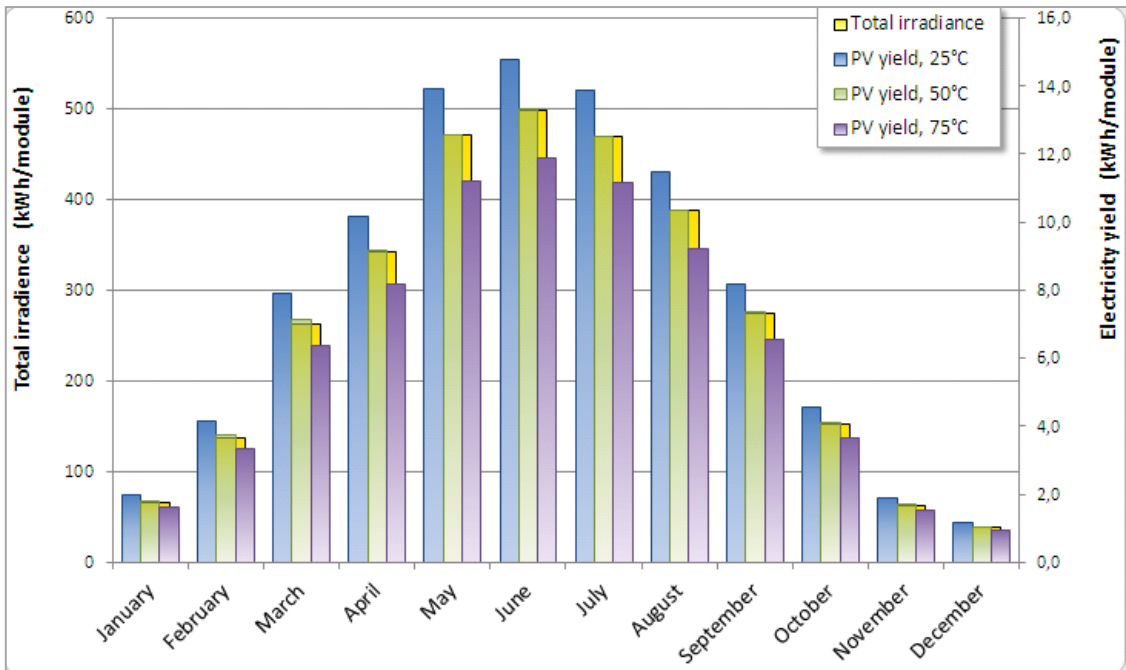


Figure 10. Example of graphical output for the PV part of a PVT.

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 m² of collector:

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

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 ²]
G_{dT} = diffuse solar radiation in the collector plane	[W/m ²]
G_T = total (beam + diffuse) solar radiation in the collector plane	[W/m ²]
$\theta_{sunNS}, \theta_{sunEW}$ = 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 ²]
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]
τ = 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 θ_i (when a simple one direction b_0 function is used) or with θ_{sunNS} and θ_{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	[-]
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either determined experimentally in a dynamic test or integrated from beam incidence angle modifier curves ref [10].

c_1 = heat loss coefficient at $(t_m - t_a) = 0$, c_1 is equal to a_1	[W/(m 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 $F'U_{wind}$	[J/(m ³ 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 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 $F'(\tau\alpha)_{en}$ 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 η_0 . This calculation is performed in an independent hidden sheet called "SS to QDT calc".

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

The annual energy gain per m² 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_{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 θ_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° , the K_b -value is calculated as (both Transversal and Longitudinal):

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

$$K_{\theta_b,i} = K_{\theta_b_EW} \text{ or } K_{\theta_b_NS}$$

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

-----**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 ($^\circ\text{C}$), $(T_{out} + T_{in}) \cdot 0.5$
- T_{cell} PV cell temperature ($^\circ\text{C}$, deviation from PV cell test performance at 25°C changes performance)
- Q_t Collector thermal output (W) for the whole module area with MPP tracking in operation (see above)
- A_a Collector module reference area (m^2), typically the aperture area.
- A_{abs} Collector absorber area (almost the same as A_a for flat plate PVT collectors, but much smaller for concentrating PVT collectors)
- A_{cell} Photovoltaic cell area (m^2), total for the module.
- $PV_{Temp\ dep}$ Temperature dependence of electric power output (for silicon cells typ. $0.4\%/^\circ\text{C} = 0.004^\circ\text{C}^{-1}$)
- 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 $100\text{-}2000\text{ W/m}^2/\text{K}$ for a well-designed PVT. It can be estimated from $C_{bond} = \lambda/d = \text{lambda cell lamination material} / \text{thickness of lamination}$
Example: Flat plate PVT with EVA encapsulation: $0.15\text{ W/m}^2/\text{K} / 0.001\text{ m} = 150\text{ W/m}^2/\text{K}$.)

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Example: Concentrating PVT using special thermal tape $0.8 \text{ W/m/K} / 0.0005 \text{ m} = 1600 \text{ W/m}^2/\text{K}$

Correction for temp drop in absorber. This relation is inserted in Eq. PVT-2 below

$$T_{\text{cell}} = T_m + Q_t/A_{\text{abs}}/C_{\text{bond}} \quad \text{Eq. PVT-1}$$

PVT cell temperature correction for power output.

$$\text{Cell}_{\text{Tcorr}} = (1 - \text{PV}_{\text{Temp_dep}} * (T_m + Q_t/A_{\text{abs}}/C_{\text{bond}} - 25)) \quad \text{Eq. PVT-2}$$

PVT electrical power output:

Parameters in PV power output model:

η_{cell} = PV module efficiency at 25C cell temperature, normal incidence to the collector 1000 W/m^2 solar radiation and with MPPT in operation (typical value $\eta_{\text{cell}} = 10\text{-}20\% = 0.10 - 0.20$)

η_{cell} can be calculated as:

$$\eta_{\text{cell}} = P_{\text{max_PV}} / (A_a * 1000) \quad 1000 \text{ comes from the } 1000\text{W/m}^2 \text{ at standard test conditions.} \quad \text{Eq. PVT-3}$$

$P_{\text{max_PV}}$ = Maximum PV output for solar radiation intensity of 1000 W/m^2 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 $P_{\text{max_PV}}$ and use data for near normal incidence and low diffuse fraction like a stationary test point to estimate $P_{\text{max_PV}}$.

$$P_{\text{max_PV}} = 1000 * Q_{\text{pv_DC}} / [(1 - \text{PV}_{\text{Temp_dep}}(T_m + Q_t/A_{\text{abs}}/C_{\text{bond}} - 25)) * (G_{\text{bT}} K_{\theta\text{b}}(\theta_i)_{\text{PV}} + G_{\text{dT}} K_{\theta\text{d_PV}})]$$

IAM incidence angle modifier dependence for PVT

Beam IAM for collectors with simple b_0 IAM dependence

$b_{0\text{pv}} = b_{0\text{thermal}}$ if no separate PV b_0 test data is available.

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

Beam IAM in the general case for collectors with more complex IAM:

$K_{\theta\text{b}}(\theta_i)_{\text{PV}} = K_{\theta\text{b}}(\theta_i)_{\text{thermal}}$ 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

$K_{\theta\text{d_PV}} = K_{\theta\text{d_thermal}}$ 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:

θ_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:

$$Q_{\text{pv_DC}} = \eta_{\text{cell}} * \text{Cell}_{\text{Tcorr}} * (G_{\text{bT}} * K_{\theta\text{b}}(\theta_i)_{\text{PV}} + G_{\text{dT}} * K_{\theta\text{d_PV}}) * A_a \quad \text{Eq. PVT-4}$$

If the equations for η_{cell} and $\text{Cell}_{\text{Tcorr}}$ are inserted in the equation above the total DC Power output is:

$$Q_{\text{pv_DC}} = P_{\text{max_PV}} / 1000 * (1 - \text{PV}_{\text{Temp_dep}}(T_m + Q_t/A_{\text{abs}}/C_{\text{bond}} - 25)) * (G_{\text{bT}} K_{\theta\text{b}}(\theta_i)_{\text{PV}} + G_{\text{dT}} K_{\theta\text{d_PV}}) \quad \text{Eq. PVT-5}$$

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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 :

PR_{sys} = 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 $PR_{\text{sys}} = 0.8$

$$Q_{\text{pv_AC}} = Q_{\text{pv_DC}} * PR_{\text{sys}} \quad \text{Eq. PVT-6}$$

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

Calculations of solar incidence angles θ_i , θ_{sunEW} and θ_{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).

$$\text{Solar_time} = ((\text{hour_day} - 0.5) \cdot 3600 + E \cdot 60 + 4 \cdot (\text{STD_longitude} - \text{longitude}) \cdot 60) / 3600 \quad \text{ref [5] [hours] (Eq. 7)}$$

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

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

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

Hour angle

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

Solar Zenith angle

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

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

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

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

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

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

(>0 means to the "west" of collector normal)

Else

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

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

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

(>0 means to the "north" of collector normal)

Else

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

Appendix

Incidence angle between the direction of the sun and collector normal for all orientations of the collector, with tilt β and azimuth γ

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

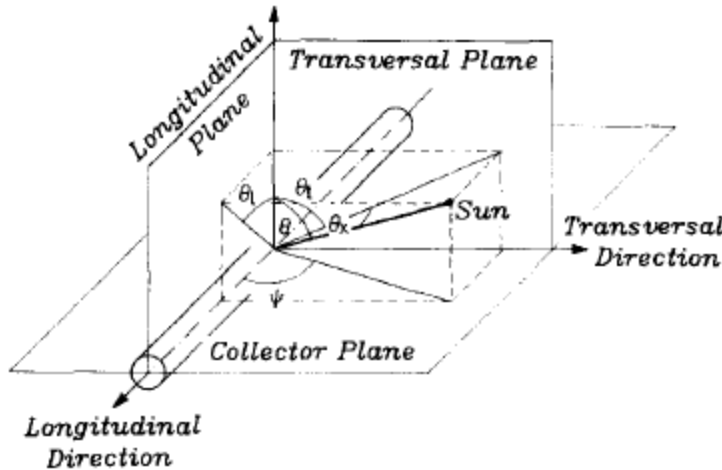


Figure 11 The definition of the biaxial incidence angles and the longitudinal and transversal planes.

**Calculation of solar radiation onto a tilted collector plane with free orientation
Tilt β and Azimuth γ including tracking surfaces.**

The notation G_{horis} , $G_{\text{b_horis}}$ and $G_{\text{d_horis}}$ 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:

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

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

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

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

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

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

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

If G_{horis} and G_{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

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

Appendix

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

Generally

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

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

”Collector information”

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

These parameter inputs are used if the collector is measured according Steady State. In some cases collectors are measured according to Steady State but the results are given in terms of η_0 , a_1 and a_2 . In that case, the collector efficiency for beam and diffuse radiation (η_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 η_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 β [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 $K_{\theta d}$ [-]

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c1, First order heat loss coefficient [W/m²K]

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/m²K and without wind.

c2, Second order heat loss coefficient [W/m²K²]

The coefficient c_2 describes the second degree of temperature dependence of the heat losses from the collector in terms of W/m²K². Corresponds to a_2 in the Steady State measurements.

c3, Wind dependence of the heat loss coefficient [J/m³K]

The coefficient c_2 describes the wind dependence of the heat losses from the collector in terms of J/m³K. 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:

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

Where b_0 is a coefficient to describe the IAM, θ 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.

Appendix

Description of the output sheet

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

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

Appendix

D. Interpolation of IAM type parameters

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

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

- a. Check that there are values entered for -90° , 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.

Appendix

E. Nomenclature

Term	Definition	Unit
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_{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_{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	$[\text{°C}]$
θ_Z	Solar Zenith angle ($=90 - \theta_H$)	
γ_s	Solar Azimuth angle (0 = south, east negative)	$[\text{degrees}]$
β	tilt angle of collector plane from horizontal	$[\text{degrees}]$
γ	Collector azimuth angle from south =0, east negative	$[\text{degrees}]$
δ	Solar Declination	$[\text{degrees}]$
ω	Solar hour angle	$[\text{degrees}]$
θ_i	Angle of incidence onto collector. (from collector normal)	$[\text{degrees}]$
ϕ	Latitude of collector and climate data location	$[\text{degrees}]$
θ_{LsunNS}	Solar Incidence angle in a vertical NS plane to the collector	$[\text{degrees}]$
θ_{TsunEW}	Solar Incidence angle in an EW plane perpendicular to the coll.	$[\text{degrees}]$
θ_{Lcoll}	Incidence angle onto coll. along the vacuum tubes or reflectors	$[\text{degrees}]$
θ_{Tcoll}	Incid. angle onto coll. perpendicular to vac. tubes or reflectors	$[\text{degrees}]$
η_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 $(t_m - t_a) = 0$	$[-]$

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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} =Longitude	Longitude of location (e.g. Stockholm -18.080) <i>Angles east of Greenwich are negative</i>	[degrees]
L_{std} =STD_longitude	Longitude of time zone (e.g. Sweden -15.0) <i>Angles east of Greenwich are negative</i>	[degrees]
E	Equation of time correcting for the eccentric path of the earth around the sun.	[minutes]
B	“Earth position” around the sun during the year 0-360 deg.	[degrees]
n = Day of year	Daynumber from the beginning of the year. (Jan 1 = 1)	[-]