

A TOOL FOR STANDARDIZED COLLECTOR PERFORMANCE CALCULATIONS INCLUDING PVT

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Abstract

A tool for standardized calculation of solar collector performance has been developed in cooperation between SP Technical Research Institute of Sweden, DTU Denmark and SERC Dalarna University. The tool is designed to calculate the annual performance of solar collectors at representative locations in Europe. The collector parameters used as input in the tool are compiled from tests according to EN12975, without any intermediate conversions. The main target group for this tool is test institutes and certification bodies that are intended to use it for conversion of collector model parameters (derived from performance tests) into a more user friendly quantity: the annual energy output. The energy output presented in the tool is expressed as kWh per collector module. A simplified treatment of performance for PVT collectors is added based on the assumption that the thermal part of the PVT collector can be tested and modeled as a thermal collector, when the PV electric part is active with an MPP tracker in operation. *The thermal collector parameters from this operation mode are used for the PVT calculations.*

1. Introduction

It is a common experience that different simulation tools do not agree as good as one could expect when comparing collector energy gains. There are many reasons for this aside from the obvious possibility of programming errors in the tools. It can for example be due to differences in the collector models used, different ways to interpret and use the collector parameters from a standard test, different operating conditions for the collector and different climate data for the same location. Even the same solar calculation software, in this case Meteonorm, was shown to give different climate data from different versions. This was an unexpected experience during the development of the tool when adding and updating the climate data. These were no huge differences, but in the range of 5% in solar radiation. The collector output difference is often larger than the difference in climate input data. Also the split of global solar radiation between beam and diffuse radiation can be changed without notice. Therefore a well defined calculation tool is very desirable.

In the competition on the solar market even a few percent difference in predicted collector output can have an influence on who will get a contract. Also in advertisement and marketing it is important to have comparable performance data for the customers.

To overcome this uncertainty that sometimes can be very large especially when applying different simulation tools to new collector designs, the Excel tool described here has been developed as a benchmark for collector output to have comparisons on a common ground. The direct compatibility to EN12975 Quasi dynamic test (QDT) results and, after applying built in corrections, also to Steady State (SS) test results, is also a big advantage. The international cooperation and agreement to use the tool within the new edition of the EN 12975 standard and in the Solar Keymark scheme rules is also an important step.

To make the calculation tool more easily accepted, the equations used in the tool are put together from the well-known solar textbook Duffie and Beckman (2006) or journal publications Braun (1983), Fisher (2004), Mc Intire (1983), Theunissen (1985). The equations are fully defined and described as a set in a document available together with the software. Also some work has been done to exactly select and define the climate input data, including ground albedo (0.2) and describe the procedure to calculate global, beam and diffuse radiation onto a fixed tilted or tracking collector plane. This is otherwise a very common reason for differences between simulation tools alone in the range of +/-10%.

The collector model used is exactly the same as in the QDT method (Quasi Dynamic Test Method) in the European standard, except that the dynamic correction term is omitted, in order to make the implementation in Excel easier. This thermal capacitance term has its main advantage during collector testing for correction

of dynamic effects during rapid variations in solar radiation. By this dynamic correction much more measurement points can be gained during a normal testing day, than with the stationary test method (SS). The thermal capacitance term has less importance for the annual performance at constant operating temperature as applied in the tool and the difference between common normal collector designs is limited.

The required calculations for "creation of missing parameters" from a stationary test (SS) compared to the QDT test method, e.g. the incidence angle modifier for diffuse irradiance or zero loss efficiency for beam radiation, are done within the tool in a standardized and reproducible way. This "SS to QDT conversion" is described and demonstrated in another paper at this conference Kovacs (2011).

The underlying equations used, for the collector model, solar radiation processing and for calculation of incidence angles relative to the collector are described as a complete validated set below, in chapter 3. This set of equations may be interesting also for other purposes, as the literature is full of different equations in this area with a variety of nomenclature and hidden limitations in application ranges. This may lead to unexpected errors when programming even simple solar energy calculations.

The tool can handle all collector designs on the market except ICS collectors (integrated collector storage) where the built in storage with a very large time delay needs a special thermal capacitance correction.

Unglazed collectors, vacuum tube collectors, low, medium and high concentrating collectors and flat plate collectors are all within the application range.

The tool is also prepared for unglazed low temperature collectors operating below the dew point of the ambient air. Presently only the climate data, but not the equations are adapted, as the model additions are not fully validated for all normal variants of these collectors.

Calculations can be performed for any collector tilt and orientation as well as for some common tracking alternatives on the market.

2. Description of the tool

Together with the tool there is a description and documentation in English, so that the tool will be as transparent as possible and allow an independent check with other tools. One can also then investigate and understand why there may be differences in results compared to other softwares.

The Excel tool has been developed within the Solar Keymark II and QAIST projects, see www.qaist.org. The tool is presently saved as an Excel 97-2003 spreadsheet and you need to activate macros in order to run it.

The tool calculates the energy output from solar thermal collectors based on weather data from four European locations: Stockholm, Würzburg, Davos and Athens. The tool can directly use parameters derived from collector tests according to EN 12975 and presented on the ESTIF / Solar Keymark homepage <http://www.estif.org/solarkeymark/>. The tool calculates the collector gain at three user defined operating temperatures which are assumed to be constant over the year. The collector tilt and orientation is free and also standard tracking options are available. It produces Energy output figures and a diagram on an annual and monthly basis as default, but hourly values can also be accessed. It is also possible to add new locations for the user. The calculation procedure is shown in five steps below (Figures 1 to 5) and finally a result output screen is shown in Figure 6.

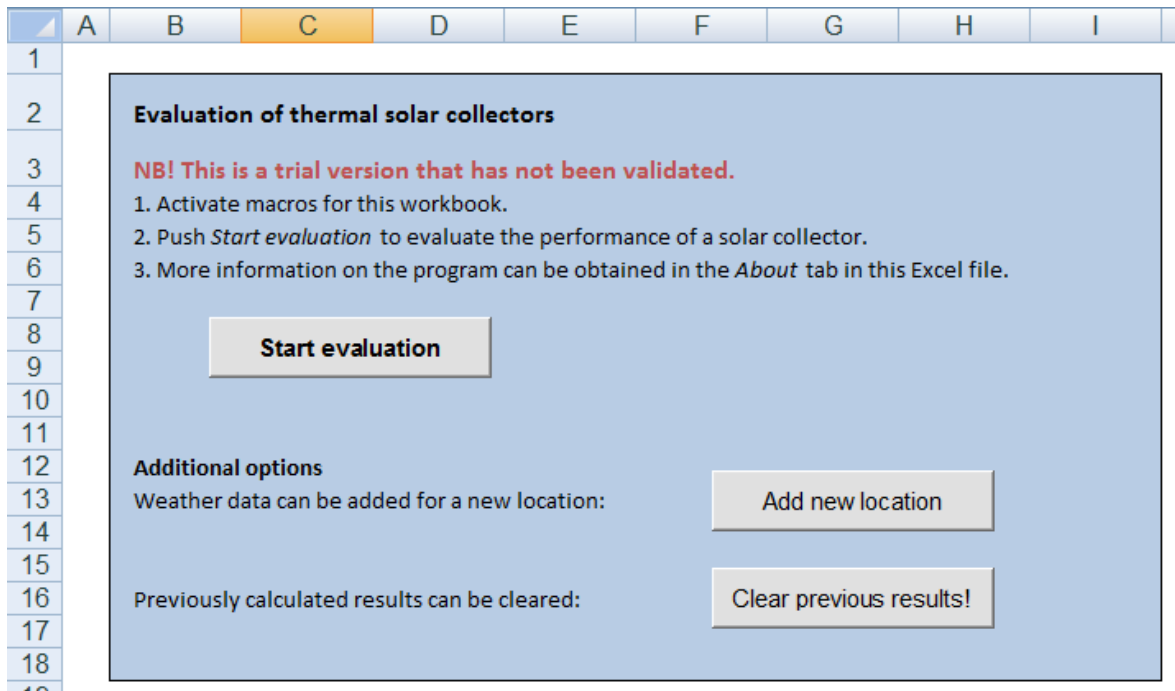


Figure 1. Step 1: Start Page for the calculation tool.

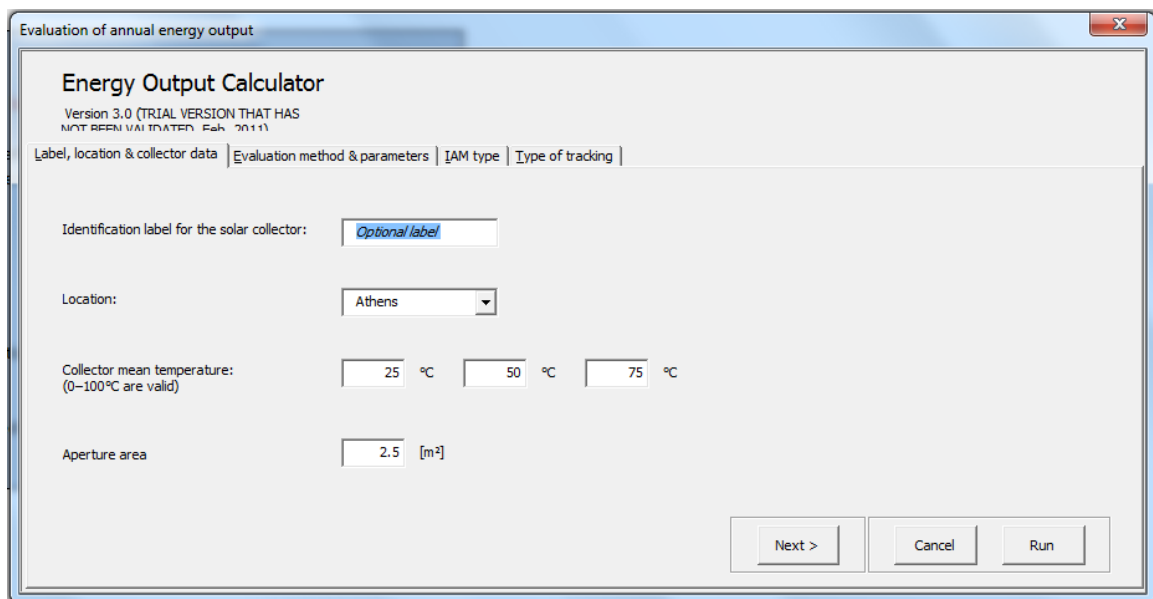


Figure 2. Step2: Id name of the run. Location/climate, operating temperatures and collector module area.

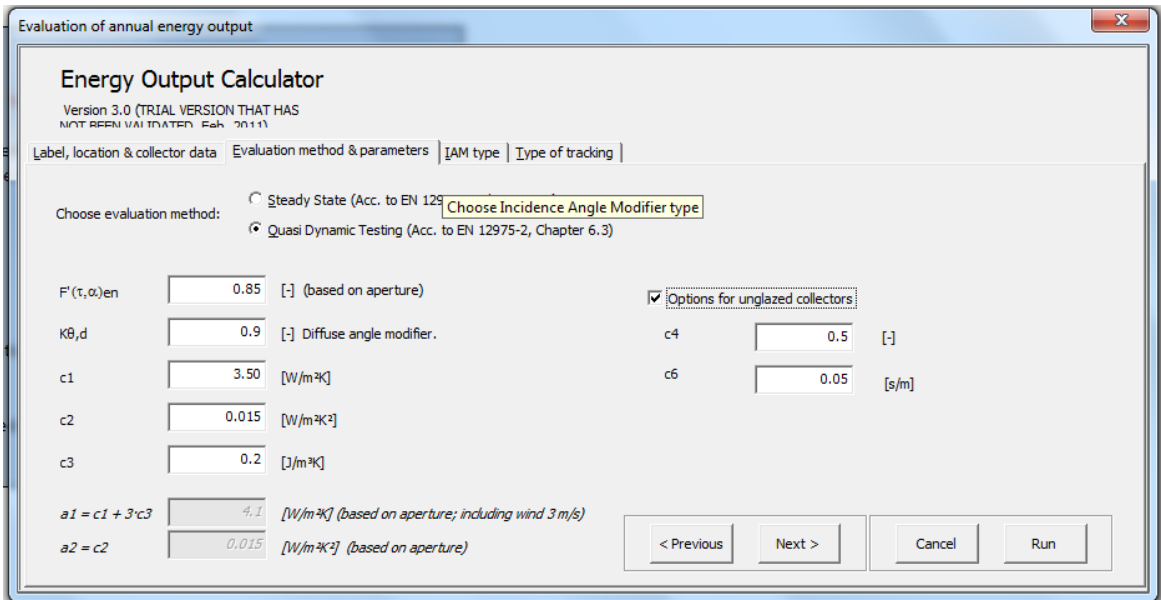


Figure 3. Step 3: Collector parameters according to EN12975 test data and Solar Keymark datasheets

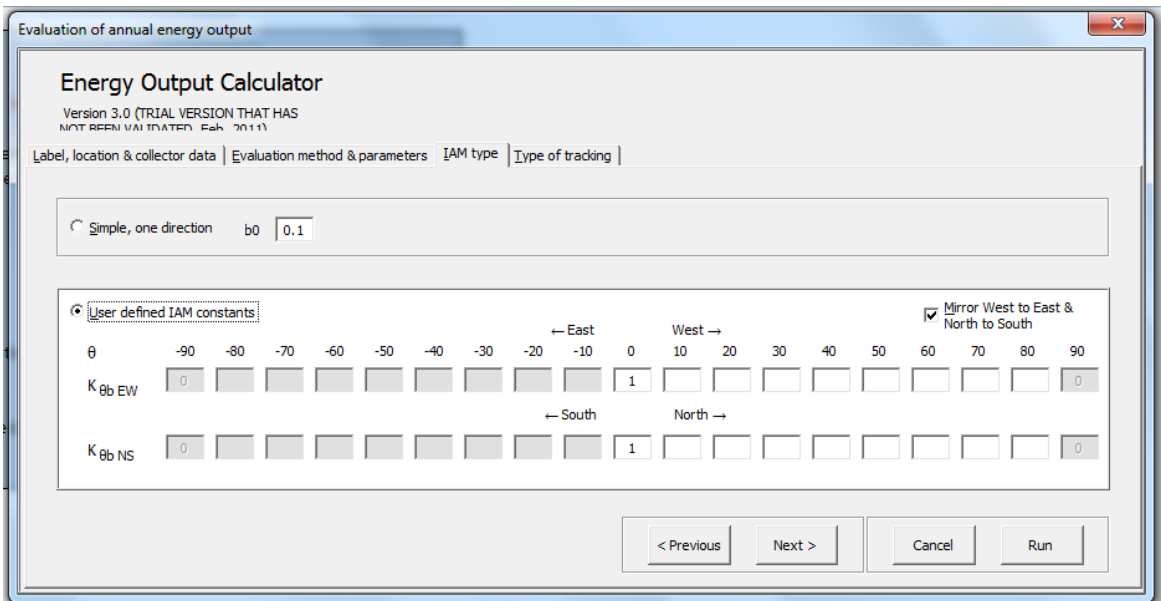


Figure 4. Step 4: Incidence angle modifier input page. Also extreme double asymmetrical collectors can be handled.

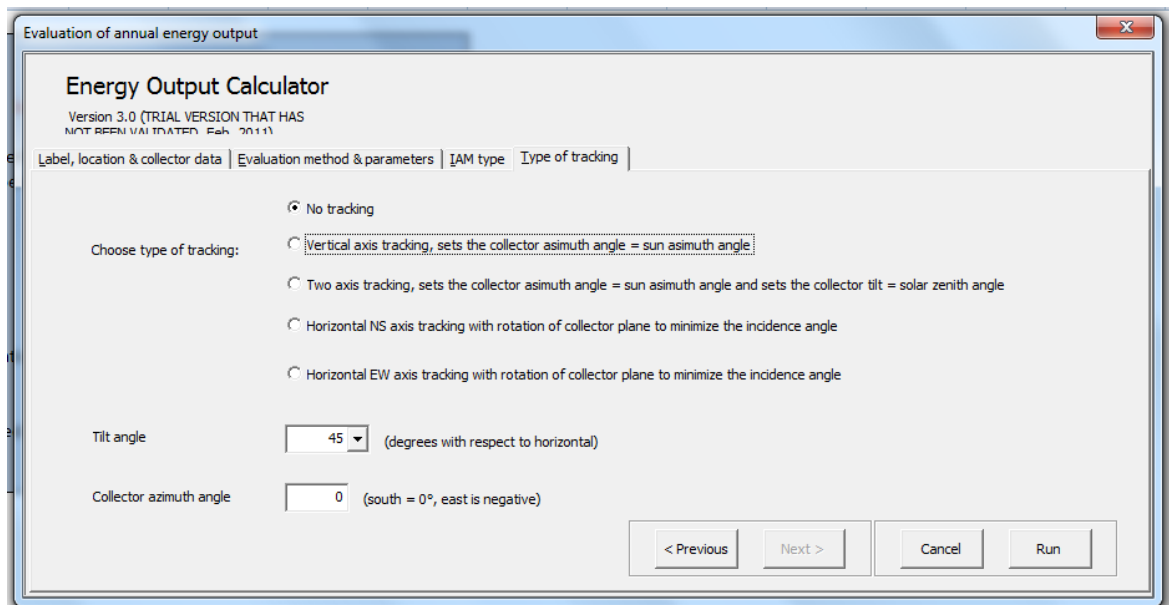


Figure 5. Step 5: Collector orientation and tracking options.

Results from the Energy Output Calculator

Version 3.0 (TRIAL VERSION THAT HAS NOT BEEN VALIDATED, Feb. 2011)

Identification label for the solar collector: Not specified

Date of evaluation: 11 August, 2011

Monthly irradiance and yield per collector unit (kWh)

| | Irradiance | Yield (three collector mean temperatures) | | |
|-------------|--------------|---|--------------|------------|
| | | 25°C | 50°C | 75°C |
| January | 269 | 132 | 82 | 45 |
| February | 264 | 120 | 70 | 35 |
| March | 317 | 147 | 81 | 35 |
| April | 375 | 189 | 115 | 60 |
| May | 416 | 225 | 145 | 81 |
| June | 425 | 236 | 154 | 84 |
| July | 453 | 257 | 171 | 98 |
| August | 476 | 276 | 191 | 113 |
| September | 440 | 263 | 185 | 115 |
| October | 368 | 206 | 134 | 72 |
| November | 265 | 138 | 86 | 44 |
| December | 226 | 112 | 67 | 35 |
| Year | 4 294 | 2 300 | 1 484 | 818 |

Location: Athens
 Longitude: -23.73
 Latitude: 38.00
 Climate data, time period: 1996-2005

Collector information (all inputs are based on aperture)

Aperture area: 2.5 m²
 Evaluation method: Quasi Dynamic Testing
 $F(\tau \alpha)_{en}$ 0.85
 $K_{0,d}$ 0.9 ($\Rightarrow \eta_0 = F(\tau \alpha)_{en} \cdot (K_{0,d}(15^\circ) \cdot 0.85 + K_{0,d} \cdot 0.15) = 0.835$)
 c_1 3.5 W/m² K ($\Rightarrow a_1 = c_1 + 3 \cdot c_3 = 4.1$ W/m² K (including wind 3 m/s))
 c_2 0.015 W/m² K² ($\Rightarrow a_2 = c_2 = 0.015$ W/m² K²)
 c_3 0.2 J/m³ K
 c_4 0.5 [-]
 c_5 0.05 s/m
 wind correction 0.5
 Type of tracking: No tracking
 IAM Type: Simple, one-direction
 $b_0 = 0.1$

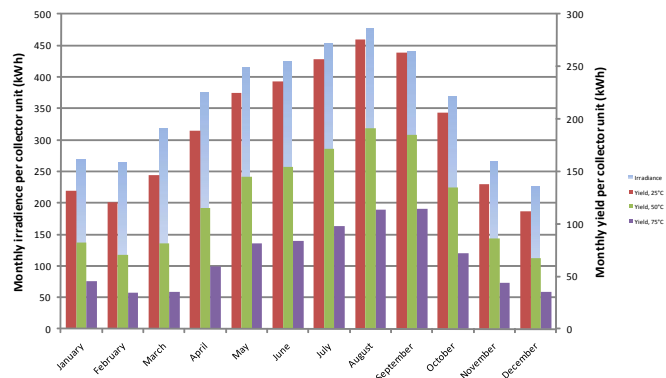


Figure 6. Step 6: Result page with solar radiation in the collector plane and collector module output. Also the main input data are documented here together with the results, for printing or saving.

As some standard uncertainty will always exist in the underlying measurements an attempt has been made to incorporate these uncertainties in the energy output figures, e.g. it will be indicated in the Solar Keymark datasheets. It is essential that the end users are aware that these uncertainties will always exist and thus it is not meaningful to take decisions on the last digit of these output figures. Current estimates give the following range of uncertainties for the collector output in different temperature ranges:

- at 25°C: ±5–10 %
- at 50°C: ±10–15 %
- at 75°C: ±20–25 %

3. Theory including electrical output of PVT collectors

3.1 Thermal Collector model including thermal output of a PVT with MPP tracker active:

Using a similar notation as in Fisher (2004) 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 a solar collector:

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

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

Variables in equation 1:

| | |
|---|---------------------|
| G_{bT} = beam solar radiation in the collector plane | [W/m 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] |
| θ_L, θ_T = Biaxial incidence angles for beam radiation onto the collector plane in longitudinal and transversal direction from the normal. Index L is usually defined along ETC tubes/reflectors and T is perpendicular to the tubes/reflectors. Index L and T are replaced by EW and NS on the input page in the tool to make sure how the collector is turned on the tilted plane. Different options are possible for some ETC and also low concentrating collectors. | |
| w_{coll} = wind speed in the collector plane | [m/s] |
| $t_m = (t_{in} + t_{out}) * 0.5$ mean fluid temperature 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 specified only to have correct thermal radiation calculations results) | [K] |
| t_a = ambient temperature close to the collector (in the shade) | [°C] |
| τ = time during measurements and simulation. | [s] |

Parameters in equation 3.1:

| | |
|--|--------------------------------------|
| $F'(\tau\alpha)_{en}$ = zero loss efficiency of the collector <i>for beam radiation</i> , at normal incidence angle | [-] |
| $K_{\theta b}(\theta_L, \theta_T)$ = incidence angle modifier for beam solar radiation. $K_{\theta b}$ varies with the incidence angles θ_i, θ_L and θ_T . Note that for many collector designs like concentrating collectors, vacuum tube's or CPC's, $K_{\theta b}(\theta)$ is generalised to $K_{\theta b}(\theta_L, \theta_T)$ where θ_L and θ_T are transversal EW and longitudinal NS incidence angles onto the collector plane. The directions are extra defined at this input area in the tool. | |
| $K_{\theta d}$ = 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 quasi dynamic test QDT or integrated from beam incidence angle modifier curves from an SS test, Pettersson (2009). | [-] |
| c_1 = heat loss coefficient at $(t_m - t_a) = 0$, c_1 is equal to $F'U_0$ | [W/(m ² K)] |
| c_2 = temperature dependence in the heat loss coefficient equal to $F'U_1$ | [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] |

The collection or set of equations for calculation of solar position, incidence angle, biaxial incidence angles and the calculation of solar radiation on a tilted surface are given below. Here it is very easy to make mistakes when collecting equations from different publications with different nomenclature and definitions.

Calculation of incidence angle modifiers

One directional incidence angle modifier.

$$K_{\theta b}(\theta_i) = 1 - b_0 \cdot (1/\cos \theta_i - 1) \quad (\text{Eq. 2})$$

User defined biaxial incidence angle modifiers.

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):

$$K_{0b,i}(73^\circ) = [70^\circ - 73^\circ / (70^\circ - 80^\circ) \cdot (K_{0b,i}(80^\circ) - K_{0b,i}(70^\circ))] + K_{0b,i}(70^\circ) \quad (\text{Eq. 3})$$

$$K_{0b,i} = K_{0b_EW} \text{ or } K_{0b_NS}$$

$$K_{0b}(\theta_i) = K_{0b_EW} \cdot K_{0b_NS} \quad (\text{Eq. 4})$$

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

The PV modelling 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 has to be chosen from experience, if not available from a PVT research test for the 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 overtemperature 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: $0.15 \text{ W/m/K} / 0.001 \text{ m} = 150 \text{ W/m}^2/\text{K}$. 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 the eq. Eq. PVT-2 below

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

PVT cell temperature correction for power output.

$$Cell_{T_{corr}} = (1 - PV_{Temp_dep} * (T_m + Q_t/A_{abs}/C_{bond} - 25)) \quad \text{Eq. PVT-2}$$

PVT electrical power output:

Parameters in PV power output model:

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

η_{cell} can be calculated as:

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

P_{max_PV} = Maximum PV output for solar radiation intensity of 1000 W/m^2 and cell temperature 25°C . 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 25°C . 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} .

$$P_{max_PV} = 1000 * Q_{pv_DC} / [(1 - PV_{Temp_dep}(T_m + Q_t/A_{abs}/C_{bond} - 25)) * (G_{bT} K_{0b}(\theta_i)_{PV} + G_{dT} K_{0d_PV})]$$

IAM incidence angle modifier dependence

Beam IAM for collectors with simple b_0 IAM dependence

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

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

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

$K_{0b}(\theta_i)_{PV} = K_{0b}(\theta_i)_{thermal}$ if no separate PV beam IAM dependence is available. Can be also 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:

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:

$$Q_{pv_DC} = \eta_{cell} * Cell_{T_{corr}} * (G_{bT} * K_{0b}(\theta_i)_{PV} + G_{dT} * K_{0d_{PV}}) * A_a \quad \text{Eq. PVT-4}$$

If the equations for η_{cell} and $Cell_{T_{corr}}$ are inserted in the equation above the total DC Power output is:

$$Q_{pv_DC} = P_{max_PV} / 1000 * (1 - PV_{Temp_dep}(T_m + Q / A_{abs} / C_{bond} - 25)) * (G_{bT} * K_{0b}(\theta_i)_{PV} + G_{dT} * K_{0d_{PV}}) \quad \text{Eq. PVT-5}$$

Note that the reference area is canceled 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 $PR_{sys} = 0.8$

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

Calculations of the solar incidence angles θ_i , θ_{TsunEW} and θ_{LsunNS} onto the collector plane

The equations to calculate the position of the sun and the incidence angle to the collector surface are described below. The nomenclature and equations follow the ones in the text book Duffie and Beckman (2006), 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).

$$\text{Solar_time} = ((\text{hour_day} - 0.5) \cdot 3600 + E \cdot 60 + 4 \cdot (\text{STD_longitude} - \text{longitude}) \cdot 60) / 3600 \quad \text{[hours]} \quad \text{Duffie\&Beckman (2006) (Eq. 5)}$$

$$E = 229.2 \cdot (0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B - 0.014615 \cdot \cos(2B) - 0.04089 \cdot \sin(2B)) \quad \text{[min]} \quad \text{Duffie\&Beckman (2006) (Eq. 6)}$$

$$B = (\text{day_of_year} - 1) \cdot 360 / 365 \quad \text{Duffie\&Beckman (2006) (Eq. 7)}$$

$$\delta = 23.45 \cdot \sin(360 \cdot (284 + \text{day_of_year}) / 365) \quad \text{Duffie\&Beckman (2006) (Eq. 8)}$$

Hour angle

$$\omega = -180 + \text{Solar_time} \cdot 180 / 12 \quad \text{(Eq. 9)}$$

Solar Zenith angle

$$\theta_Z = \arccos(\cos \phi \cdot \cos \omega \cdot \cos \delta + \sin \phi \cdot \sin \delta) \quad \text{Duffie\&Beckman (2006) (Eq. 10)}$$

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

$$\gamma_s = \text{SIGN}(\omega) \cdot | \arccos [(\cos \theta_z \sin \phi - \sin \delta) / (\sin \theta_z \cos \phi)] | \quad \text{Duffie\&Beckman (2006) (Eq. 11)}$$

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

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

$$\theta_{\text{TsunEW}} = \arctan [\sin \theta_z \cdot \sin (\gamma_s - \gamma) / \cos \theta_i] \quad \text{Theunissen (1985) (Eq. 12)}$$

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

Else

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

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

$$\theta_{\text{LsunNS}} = - (\arctan [\tan \theta_z \cdot \cos (\gamma_s - \gamma)] - \beta) \quad \text{Theunissen (1985) (Eq. 13)}$$

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

(note absolute value signs removed for handling of "double asymmetric" collectors as some CPC:s)

Else

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

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

$$\theta_i = \arccos [\cos \theta_z \cdot \cos \beta + \sin \theta_z \cdot \sin \beta \cdot \cos (\gamma_s - \gamma)] \quad \text{Duffie\&Beckman (2006) (Eq. 14)}$$

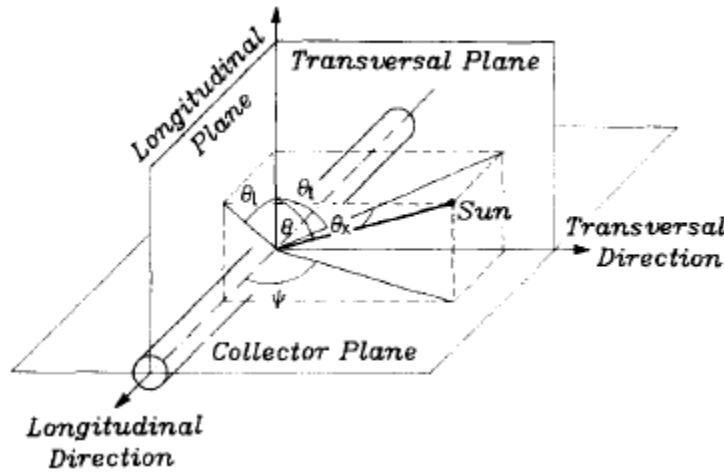


Figure 7. The definition of the biaxial incidence angles and the longitudinal and transversal planes. Theunissen (1985)

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 and G_{on} is used for extraterrestrial solar radiation on horizontal surface respectively extraterrestrial radiation in the normal direction to the sun.

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

$$G_T = G_{\text{b_horis}} \cdot R_b + G_{\text{d_horis}} \cdot A_i \cdot R_b + G_{\text{d_horis}} \cdot (1 - A_i) \cdot 0.5 \cdot (1 + \cos(\beta)) + G_{\text{horis}} \cdot \rho_g \cdot 0.5 \cdot (1 - \cos(\beta)) \quad \text{(Eq. 15)}$$

$$G_{\text{bT}} = G_{\text{b_horis}} \cdot R_b \quad \text{and} \quad G_{\text{dT}} = G_T - G_{\text{bT}} \quad \text{(Eq. 16)}$$

Note here 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.

$$R_b = \cos(\theta_i) / \cos(\theta_z) \quad \text{(Eq. 17)}$$

R_b is the conversion factor between the normal direction to the sun and the collector plane.

Conditions: $\theta_i < 90$ and $\theta_z < 90$ else $R_b = 0$

$$A_i = G_{b_horis} / G_o \quad (\text{Eq. 18})$$

Anisotropy index (how large fraction of the diffuse radiation that is circumsolar)

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

$$G_o = 1367 \cdot (1 + 0.033 \cdot \cos(360 \cdot n / 365)) \cdot \cos(\theta_z) \quad (\text{Eq. 19})$$

If G_{horis} and G_{d_horis} are given in the climate file (previous version of the tool) $G_{b_horis} = G_{horis} - G_{d_horis}$

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

Note: One second order effect to consider here is that the second term (=circum solar radiation) in the G_T equation above should be added to the beam radiation in the collector plane for most collectors, also when calculating the output power. But for high concentrating collectors this circumsolar diffuse radiation may not be accepted as beam radiation and will miss the absorber. This is not explained fully in the simulation literature and needs some attention and further validation in special case 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 transformations 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 orientation angles of the collector, it is now quite easy to specify the basic tracking options:

1. Freely oriented but fixed collector surface with tilt β and azimuth γ : No equation changes.
2. Vertical axis tracking with fixed collector tilt β : Set azimuth $\gamma = \gamma_s$ all the time.
3. Full two axis tracking: Set the collector tilt $\beta = \theta_z + 0.001$ and collector azimuth $\gamma = \gamma_s$ all the time. The addition of 0.001 is done 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 $\beta = \arctan(\tan(\theta_z) \cdot |\cos(\gamma - \gamma_s)|)$ and collector azimuth $\gamma = -90$ if $\gamma_s < 0$ and $\gamma = 90$ if $\gamma_s > 0$.
5. Horizontal EW axis tracking with rotation of collector plane to minimize the incidence angle. Collector tilt angle $\beta = \arctan(\tan(\theta_z) \cdot |\cos(\gamma_s)|)$ and collector azimuth $\gamma = 0$ if $|\gamma_s| < 90$ and $\gamma = 180$ if $|\gamma_s| > 90$.

4. Validation of the Excel tool

Collector input data for a typical extreme ETC collector with round absorbers is used, same as in Kovacs (2011). The TRNSYS collector variant is also here Type 832 which is exactly the same as Type 136 except that 136 has also condensation included. It was used because the input of an asymmetric IAM was easier in type 832. The type 136 has a more scientific input as a matrix of IAM:s that could give a minimal source of uncertainty for this validation.

Results for Stockholm and Athens are given below. As can be seen the differences in annual sums are very small. It should also be mentioned that TRNSYS calculates dynamically with a thermal capacitance of the collector that cannot be set to exactly zero and gives a small theoretical difference. The "testexcelark BP" given for Stockholm is an intermediate Excel tool to check the basic formulas before and during programming of the SP Excel.

Table 1. Validation results for Stockholm and Athens both solar radiation and Collector output in [kWh].

| Stockholm Metenorm Climate | | | | |
|----------------------------|------------|-------|-------|-------|
| ETC validation | Gtilt 45de | 25.0 | 50.0 | 75.0 |
| Excel SP version 3 | 1 166 | 876 | 728 | 580 |
| Testexcelark BP | 1166 | 876 | 728 | 580 |
| TRNSYS Type 832 | 1168 | 875 | 726 | 578 |
| Excel SP/TRNSYS | 0.998 | 1.001 | 1.003 | 1.002 |

| Athen Metenorm Climate | | | | |
|------------------------|------------|-------|-------|-------|
| ETC validering | Gtilt 45de | 25.0 | 50.0 | 75.0 |
| Excel SP version 3 | 1 718 | 1 377 | 1 198 | 1 004 |
| TRNSYS Type 832 | 1713 | 1379 | 1199 | 1005 |
| Excel SP/TRNSYS | 1.003 | 0.998 | 0.999 | 0.999 |

To give an impression of the accuracy of the monthly values of solar radiation on horizontal and 45 deg tilted surface and collector output figures 2 and 3 below are shown.

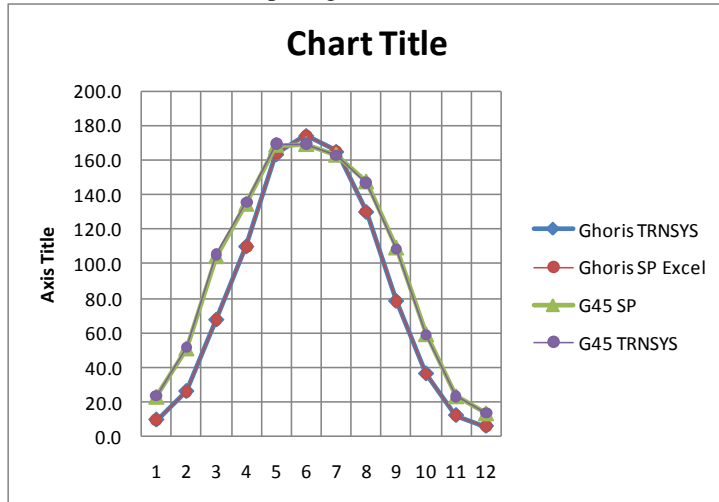


Figure 8. Comparison of total solar radiation on horizontal and 45 degree tilted surface

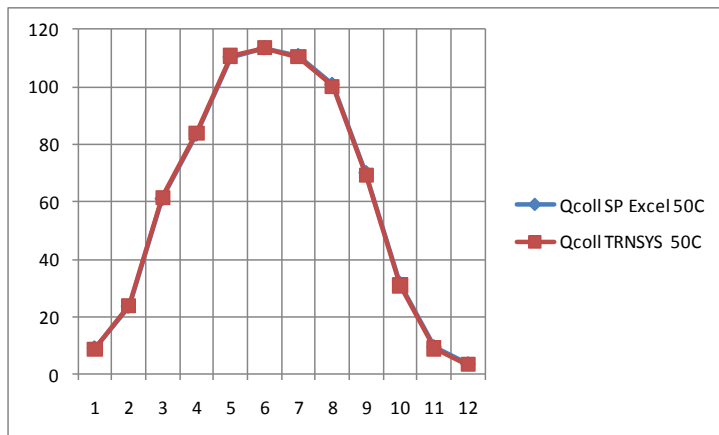


Figure 9. Comparison of Energy output for 50C operating temperature Stockholm

Table 2: Collector input data for the ETC collector:

| ETC | |
|-----------------|------|
| F'ta_en | 0.65 |
| Ktätadiff | 1.22 |
| b0 | 0 |
| c1 (tm-ta) | 1.5 |
| c2 (tm-ta)^2 | 0.01 |
| c3 wind*(tm-ta) | 0 |
| c4 (EL-Ta^4) | 0 |
| c5 dTm/dt | 0 |
| c6 wind*Gtot | 0 |
| Korrektion vind | 0.5 |

Assymmetric Incidence angle Input data for the ETC collector:

| | | | | | | | | | | | | | | | | |
|----------|-----|------|------|------|------|------|-------|------|------|---|------|------|-------|------|------|------|
| Angle, ° | -90 | -80 | -70 | -60 | -50 | -40 | -30 | -20 | -10 | 0 | 10 | 20 | 30 | 40 | 50 | 60 |
| K b, T | 0 | 0.88 | 1.76 | 1.76 | 1.73 | 1.41 | 1.275 | 1.14 | 1.07 | 1 | 1.07 | 1.14 | 1.275 | 1.41 | 1.73 | 1.76 |
| K b, L | 0 | 0.35 | 0.7 | 0.84 | 0.92 | 0.97 | 0.985 | 1 | 1 | 1 | 1 | 1 | 0.985 | 0.97 | 0.92 | 0.84 |

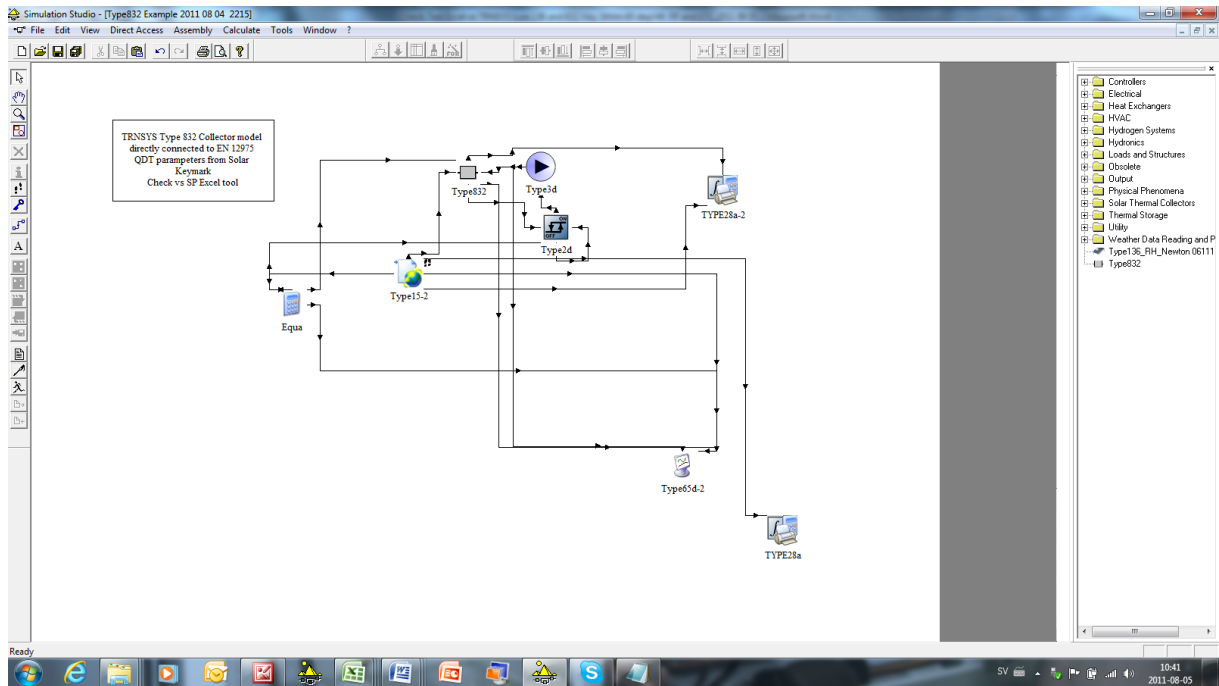


Figure 10: TRNSYS 16 Studio setup for type 832 validation calculations

5. Discussion and conclusions

A well documented and transparent calculation tool is created for calculation of exactly comparable collector energy output values under well defined conditions for the European market.

EN12975 test data from both steady state and quasi dynamic testing can be used directly in the tool.

The tool is not intended to replace detailed system simulation as the operating conditions of constant temperature are just an approximation of the conditions in a real system.

A TRNSYS model type 832 is also available with exactly the same model setup for the use in system simulation. This model has been used to validate the excel tool.

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