

A NEW TOOL FOR STANDARDIZED COLLECTOR PERFORMANCE CALCULATIONS

Bengt Perers¹, Peter Kovacs², Marcus Olsson², Martin Persson² Ulrik Pettersson²

¹ Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark and
SERC Dalarna University, Borlänge, Sweden.

² SP Technical Research Institute of Sweden, Borås Sweden.

Abstract

A new tool for standardized calculation of solar collector performance has been developed in cooperation between SP Borås Sweden, DTU Denmark and SERC Dalarna University. The tool is designed to calculate the annual performance for a number of representative cities in Europe on the basis of parameters from collector tests performed according to EN12975, without any intermediate conversions. The main target group for this tool is test institutes and certification bodies that intend to use it for conversion of collector model parameters derived from performance tests, into a more user friendly quantity i.e. the annual energy output. Energy output both per m² and per collector module can be calculated.

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 wrong programming in the tools. It can be 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 as some examples. Even the same solar calculation software like Meteororm can give different climate data between different versions that was an unexpected experience during the development of the tool and adding and updating climate data. 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 changing 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 (2006) QDT test results and with built in corrections also SS test results, is also a big advantage. The international cooperation and agreement to use the tool within EU 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 c_5 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 short term 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 applied in the tool and the difference between common normal collector designs is limited. In a full system simulation c_5 can still be used from a QDT test and then added to the

effect of capacitance of piping, valves pumps etc. in the collector loop. This can be an important factor to optimize together with the flow rate and insulation in a system.

The required calculations for correction of 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. Tracking limitations and shading between throughs in a collector module is not implemented yet in the tool. The shading can be taken care of by the incidence angle modifier if a complete module, with several throughs, is tested.

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.quaist.org . The tool is presently saved as an Excel 97-2003 spreadsheet and a activation of macros is needed 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 and climates by the user.

Some extra effort has been spent to define the biaxial incidence angle inputs, in a consistent way, as the traditional wordings transversal and longitudinal can be misleading. Especially when the same collector is turned on the mounting plane that can be the case for some ETC- and low concentrating collectors. The software need the parameters as they are seen from the “sun” so the collector independent indices EW (East West) and NS (North South) are introduced. Also the case of double asymmetrical collectors is taken care of. For example for collectors that have a cut off angle at a certain apparent solar altitude (an angle similar to the profile angle). They are mounted in different directions and this has a large effect on the annual performance.

The calculation procedure is shown in 5 steps below (figure 1 to 5) and finally a result picture is shown figure 6.

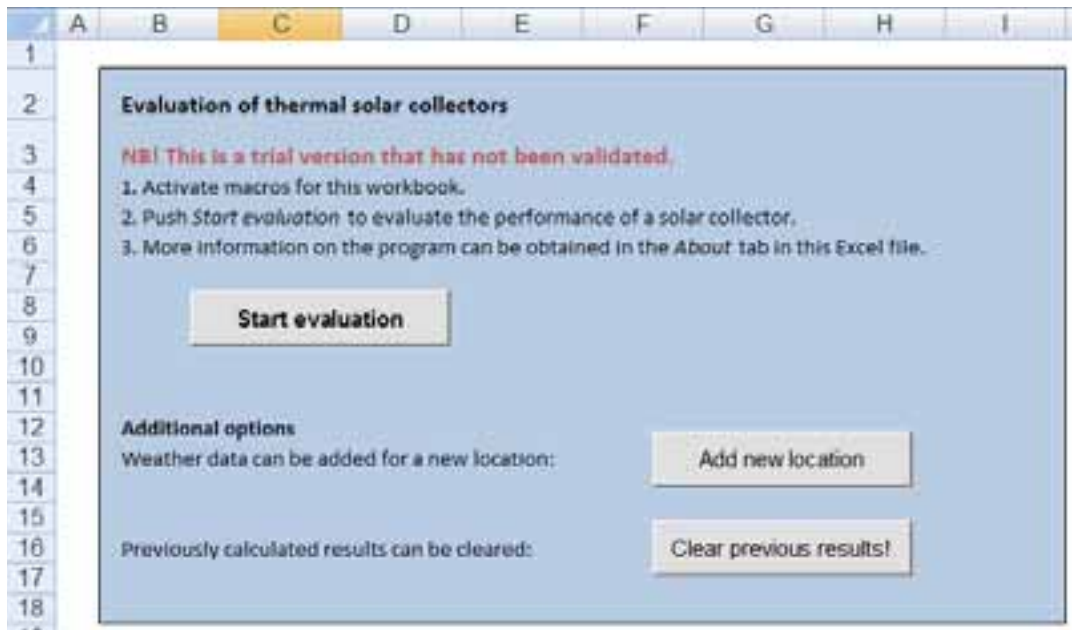


Figure 1. Step 1: Start Page for the calculation tool.

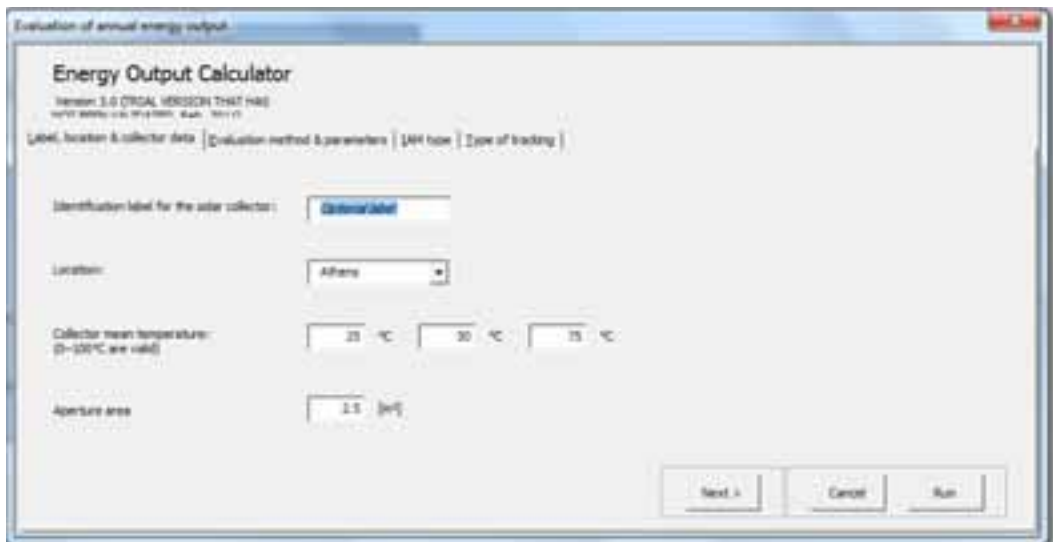


Figure 2. Step2: Id name of the run. Location/climate, operating temperatures and collector module area.



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



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

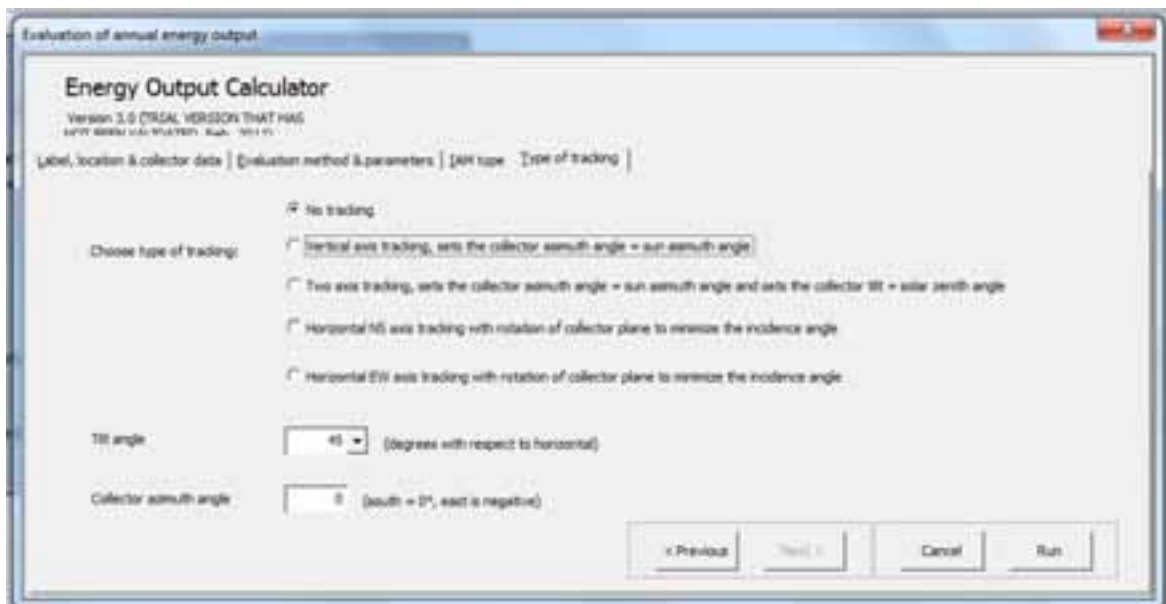


Figure 5. Step 5: Collector orientation and tracking options.

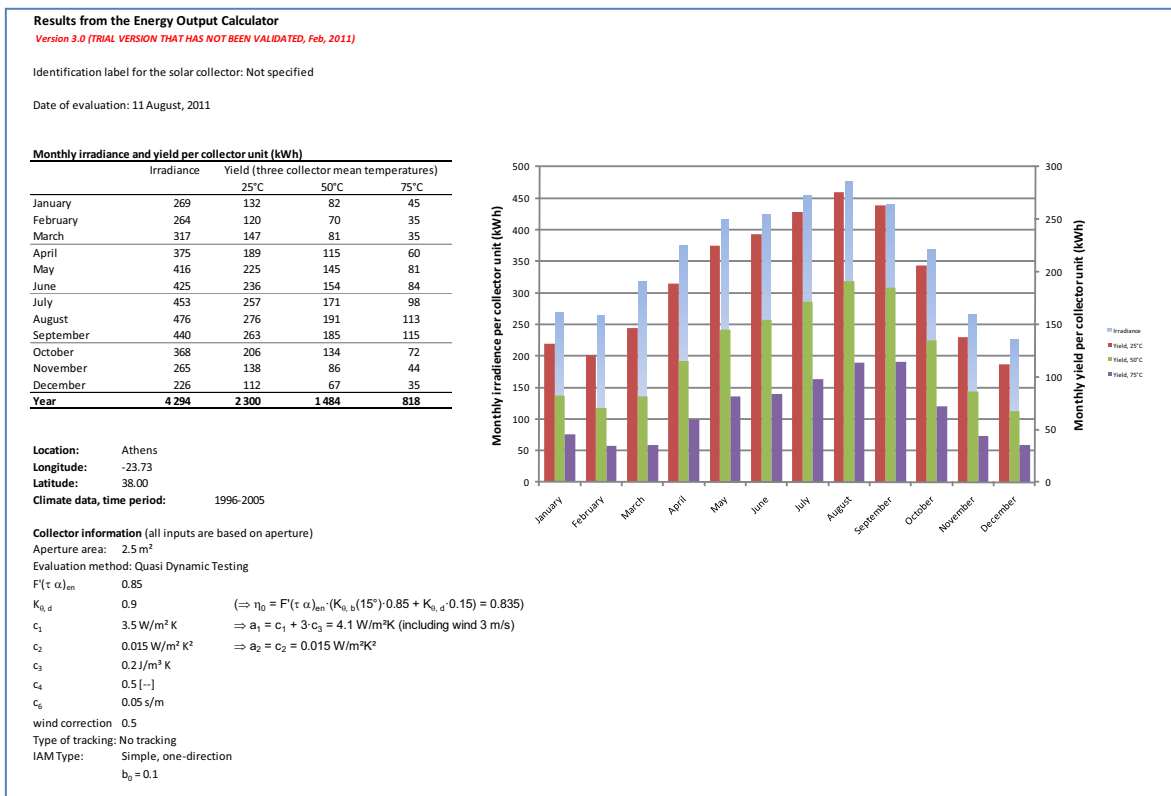


Figure 6. Step 6: Result page with solar radiation in the collector plane and collector module output. Also the main input data are documented here together with the results, for printing or saving.

3. Theory

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:

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

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/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]

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. This can be the case for some ETC and also low concentrating collectors.

u = 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/m²]

T_a = ambient temperature close to the collector (in the shade) [K]

(Kelvin is specified only to have correct thermal radiation calculations results)

t_a = ambient temperature close to the collector (in the shade) [°C]

τ = time during measurements and simulation. [s]

Explanation of parameters in equation 1:

$F'(\tau\alpha)_{en}$ = zero loss efficiency of the collector <i>for beam radiation</i> , at normal incidence angle	[-]
$K_{0b}(\theta_L, \theta_T)$ = incidence angle modifier for beam solar radiation. K_{0b} 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, $K_{0b}(\theta)$ is generalised to $K_{0b}(\theta_L, \theta_T)$ 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_{0d} = 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 $F'\varepsilon$	[-]
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]

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.

$$K_{0b}(\theta_i) = 1 - b_0 \cdot (1/\cos \theta_i - 1) \quad (\text{eq. 2})$$

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):

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

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

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

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 follows 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).

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

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

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

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

Hour angle

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

Solar Zenith angle

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

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

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

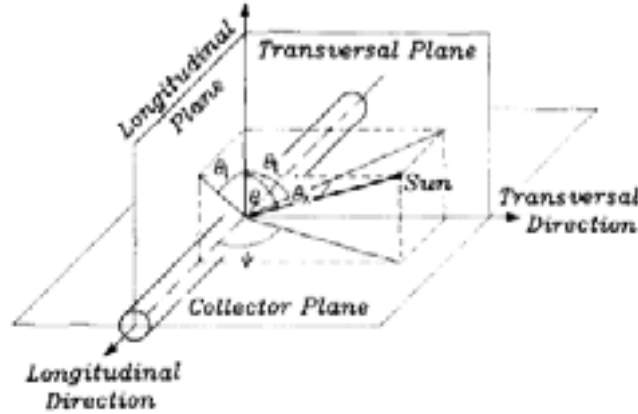


Fig. 7: The solar and collector biaxial geometry from Theunissen (1985)

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_{b_horis} and G_{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 rad. in the normal direction to the sun.

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

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

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

Note here G_{bT} does not include the circumsolar diffuse radiation that most collectors, except high concentration 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 the and 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)

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

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

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

Freely oriented but fixed collector surface with tilt β and azimuth γ : No equation changes

Vertical axis tracking with fixed collector tilt β : Set azimuth $\gamma = \gamma_s$ all the time

Full 2 axis tracking: Set the 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.

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 $\gamma_s \geq 0$

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 $|\gamma_s| \geq 90$

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 climate here is slightly different as there was a change in the meteororm data used for the Excel sheet and also the ground albedo is changed to 0.2 instead of 0.3 used above. The TRNSYS collector variant is also here Type 832 the is exactly the same as Type 136 except that 136 has also condensation included. The input of asymmetric IAM was easier in this case for 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 can not be set to exactly zero and gives a small theoretical difference. The "testexcelark BP" given for Stockholm is a 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 figure 2 and 3 below are shown.

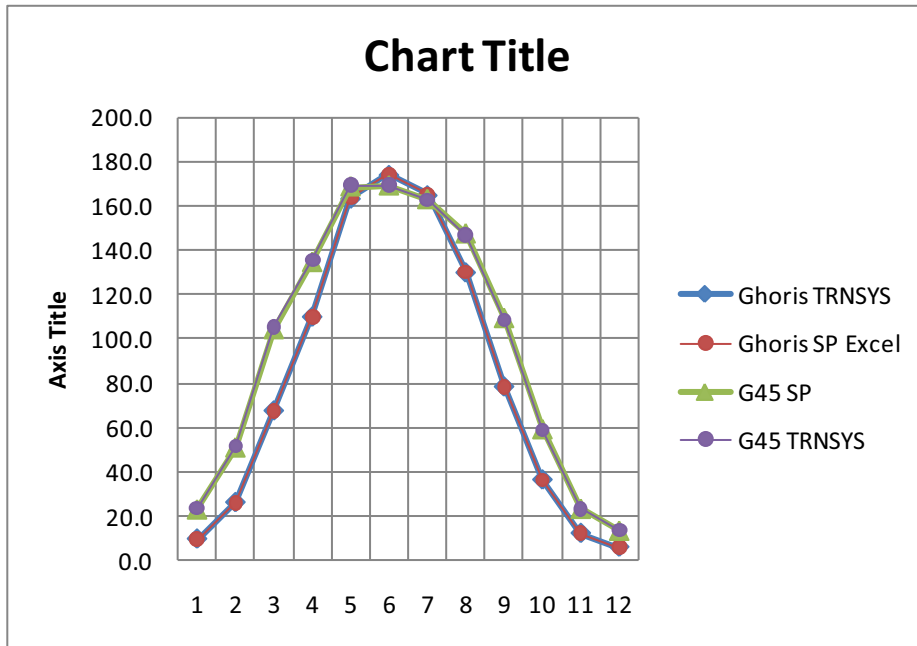


Figure 8. Comparison of total solar radiation on horizontal and 45 degree tilted surface

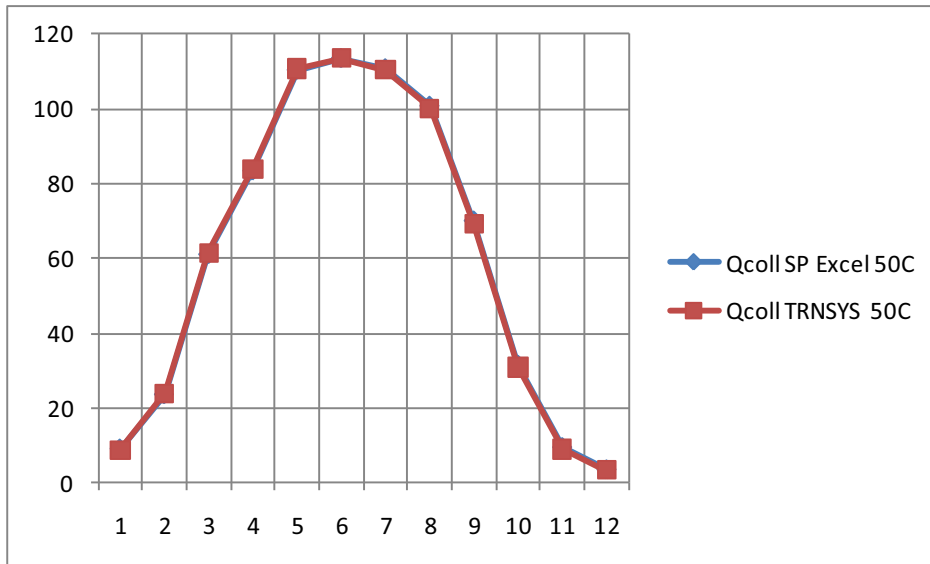


Figure 9. Comparison of Energy output for 50C operating temperature Stockholm. (The curves overlap so accurately that only the red TRNSYS can be seen clearly)

Tab. 2: Collector input parameters 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

Tab. 3: Asymmetric 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

Below is shown the TRNSYS setup in Visual Studio for the validation of the calculation tool. The type 832 is used that has been continuously developed within IEA SH&C Task 26 and 32 and now will be used in IEA 44 with some additions. The collector model programming has all the time followed the EN 12975 standard so that the collector parameters from test can be used directly even without TRNSYS unit conversions. The climate data is from the same Meteororm version 6.1 but added to TRNSYS in the form of a TMY file.

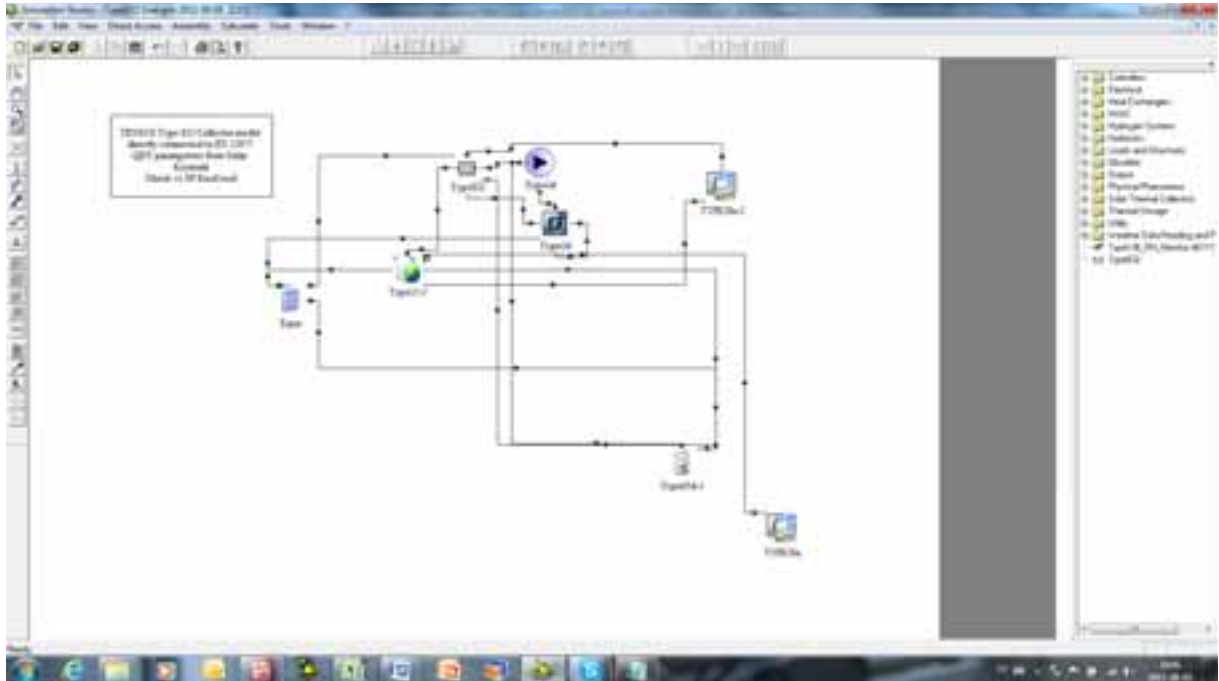


Figure 10: TRNSYS 16 Studio setup for type 832 validation calculations

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 stationary SS testing and quasi dynamic testing QDT can be used directly in the tool.

The tool is not intended to replace detailed system simulation, as the operating conditions of constant temperature is just an approximation of the conditions in a real system to have a well defined common ground for comparisons.

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.

In the future upgrades of the tool are possible to cover unglazed collectors that are operating below the dew point. Also PVT (Photovoltaic Thermal collectors) and Air collectors are on the list. For concentrating collectors tracking limitations and internal shading could be added.

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