Open Source Modeling of Solar Process Heat Systems

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Abstract

In order to establish the profitability of a solar thermal plant for their processes, industrial companies currently must come up with substantial financial means and a significant time budget. It would be more convenient to have an easy-to-handle open source software, providing simple, fast, and yet sufficiently accurate estimates of the energetic and financial performance of potential solar heating projects. With such a software, the inhibition threshold could be lowered, just as the diffusion of eco-friendly solar thermal energy technology into the industrial heat production market could be increased.

This work shows first steps towards the development of an Excel-based tool with open source Visual Basic code. This tool will be capable of calculating solar thermal heat supply from stationary and tracking collectors, based on hourly irradiance data, and for flexible heat demand profiles. No knowledge and experience in solar thermal energy studies will be required to use it. The results will be self-explanatory and contain information about feasibility and efficiency of the simulated process. Profiteers of this work are engineering firms and companies that are looking for fast, location-dependent assessment of solar thermal collector gains. The tool can as well be used and further developed by students and researchers.

First evaluation runs have shown minor deviations to established simulation programs of less than 10 % for the first steps of solar thermal energy gain calculations.

Keywords: SolGain, solar thermal process heat, SHIP, open source system simulation, Microsoft Excel

1. Introduction

Melting glaciers and risings in average temperatures all around the world are an undeniable fact that there is a climate change due to the immense amount of carbon dioxide and other greenhouse gas emissions during the last century. The target of current political debates is to reduce the tempo of the change in order to preserve the current living conditions on earth. A huge factor of these considerations are greenhouse gas neutral renewable energies for heat production such as solar and geothermal power as well as biofuels. While geothermal power is location dependent and biofuel production requires large amounts of water, solar thermal heat needs a space of rooftop or ground area of a couple square meters, dependent on the process. Once installed, solar thermal plants deliver satisfying amounts of heat for a wide range of processes at low maintenance effort.

Reducing costs is a constant aim of a company to increase profitability. The investment costs for solar thermal plants are higher than those for boilers running on fossil fuels, and with the current oil price it is a simple decision, what system to choose. Another factor might be a lack of knowledge amongst the management of companies about the possibilities of solar thermal power. To gain insight, an investment in terms of time and consulting money has to be made. The project described here aims to assist to generate and spread free and appropriate knowledge about the feasibility of solar thermal plants between companies, universities and private persons.

2. Aims of the tool

There is a variety of tools to calculate the energy outcome of solar thermal plants, e.g. Polysun [1], T*Sol [2] and TRNSYS [3], but they are either expensive or complex and require experience. Also the code and models aren't always editable for other researchers to test new developed collector or solar-loop models. T*Sol has a secured code and a limited amount of fixed systems. The hydraulics are not editable. Weather data is provided and the interface is simple. The code in Polysun cannot be edited for research reasons either. Pre designed systems can be selected or systems can be self-designed with given components and tested with given climate data. Compared to TRNSYS the user interface is more clearly and intuitive. TRNSYS requires experiences in the handling of simulation software. The user surface is comparable with Simulink. Ideally SolGain will contain advantages of all described software: Pre

designed systems, open source code, intuitive handling, and a high accuracy. Additionally it will be free of charge.

This work is on the other hand on developing a tool called "SolGain" that is free and easy to use with an open source code and specialized on processes for industrial processes. The programming language is Visual Basic, which is used worldwide in every sector and thus understandable by many target audiences. The handling shall be straightforward, self-explanatory and should need no experience in the field of solar thermal energy studies. Same requirements account for the results with clear labeled tables and graphs that are precise enough to justify further investments in this direction by a company. An elementary illustration of the tool is displayed in Figure 1.
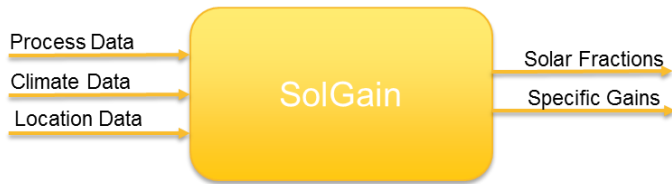

Figure 1: System boundary of the SolGain tool with input parameters and outputs

A similar approach as SolGain has been started by M. Frasquet [4] by designing a "Solar heat for industrial processes online calculator" (SHIPcal). The idea of SHIPcal is to store the software on a server that can be accessed online. Inputs will be made through a web page and the results will be sent via e-mail. The difficulty is the provision of climate data, since they can't be entered at this tool, so it is not usable for any place in the world. SolGain will also include only a small range of climate data, but it will supply the user with free or fair sources for weather data in the TMY-Format [5] that can be fed to the program and used for calculations. This step is a complication compared to SHIPcal and other software but with good explanations and the base set of data the disadvantage is modest.

The tool will be available as a downloadable Excel-file free of charge from the website of the Solar Thermal Energy Research Group (STERG) of Stellenbosch University. Since Microsoft Excel is commonly used by companies and universities, the costs of purchase for this program are neglected. The reason for the limited distribution of Visual Basic for engineering purposes is its limitations in advanced calculations. For a rough simulation like it is made in SolGain its features are sufficient and its simplicity is decisive and an advantage in this case.

3. User interface and input

Once opened the file will show a worksheet with descriptions and buttons that will lead to user forms for data entry, parameter

fixing or start a simulation run, assuming that macro calculation is active. Beside this sheet there is a summary work sheet where adaptions of single values can be made without repeating the whole entry process. The amount of data that has to be supplied by the user should be minimal and for every field left open SolGain will suggest default standard values.

The data that has to be provided by the user is divided into three main groups: Location data, climate data and process data. Table 1 features the data input for every category.

Location Data	Climate Data	Process Data
-Latitude φ -Hemisphere -A	-G_d -$G_b(DNI)$ -T_a	-$\dot{M}$ or $\dot{Q}$ -$T_{in,p}$ -$T_{out,p}$ -$c_{p,fl}(T)$ -Load profile

Table 1: User input data of SolGain

The Location Data consists of the latitude, the hemisphere and the area size A that is available. The entry of climate data will be made via an additional Excel-file in a predefined format, which contains data sets for the global diffuse radiation G_d, the direct normal irradiation G_{bn}, and the ambient Temperature T_a in hourly averaged values for a whole meteorological reference year of 8760 hours. The process data contain the mass flow $\dot{M}$ of a defined heat carrier with a heat capacity $c_{p,fl}$, the inlet T_{in} and outlet temperature T_{out} of the heat sink (process) as well as the energy needed $\dot{Q}$. In case the heat demand isn't constant a load profile (LP) can be added to the calculation. Optional inputs are parameters of certain collector types or other calculation parameters that are otherwise predefined by the program.

4. Calculation Steps

4.1 Irradiation on a tilted collector plain

The calculation of the sun position in SolGain follows the Excel model of the National Oceanic and Atmospheric Administration of the United States (NOAA) [6]. To reduce the calculation effort all adjustments concerning the longitude and the year are left out, since the inaccuracy and the effects on the end results are marginal. A day in SolGain is represented by 24 hours that aren't equal to the local time of a specified location, which might cause some shifting of results for fluctuating LP's that have to be considered in future steps. With these simplifications the following equations for the hour angle ω and the declination δ are determined [7, p. 14].

$$\omega = (h_{local} - 12) * (\frac{360}{24})$$

$$\delta = 23.4 * \sin(360 * \frac{EQ + d_{local} - 1}{365})$$

For the calculation of ω the local hour of the day h_{local} in a 24 hour day is needed. The term of 23.4 stands for the Tropic of Capricorn or Tropic of Cancer and EQ is calculated from the day of equinox. For locations on the northern hemisphere EQ is 284 which stands for the 22nd of March and for locations on the southern hemisphere EQ is 101 which is the 21st of September. With these values and the latitude φ, the zenith angle of the sun θ_s and the azimuth ϕ_s of the sun can be calculated for each hour of the day [6].

$$\theta_s = \sin^{-1}(\cos(\delta) * \cos(\omega) * \cos(\varphi) + \sin(\delta) * \sin(\varphi))$$

$$\phi_{s,am} = MOD(\frac{\cos^{-1}\left(\frac{(\sin(\varphi) * \cos(90 - \theta_s)) - \sin(\delta)}{\cos(\varphi) * \sin(90 - \theta_s)}\right) + 180}{360})$$

$$\phi_{s,pm} = MOD(\frac{540 - \cos^{-1}\left(\frac{(\sin(\varphi) * \cos(90 - \theta_s)) - \sin(\delta)}{\cos(\varphi) * \sin(90 - \theta_s)}\right)}{360})$$

The MOD-function returns the remainder of dividend/divisor, in this case a number between 0 and 360. The height of the sun is the angle between the surface of the earth and the sun beams on the location of view. Negative values indicate no visible sun and 90° means that the sun is in zenith. The azimuth describes the horizontal direction of the sun. In the southern hemisphere the azimuth is 0°/360° if the sun is in a right angle to the equator in the south and 180° if the sun is in a right angle to the north.

The calculation of the angle θ between the surface of a tilted plain and the sun beams depends on the tilt of the collector β, the zenith angle of the sun, the azimuth of the sun and the orientation of the collector [7, p. 15].

$$\theta = \cos^{-1}(\cos\theta_s * \cos\beta + \sin\theta_s * \sin\beta * \cos(\phi_s - \gamma))$$

The radiation on a plane G_t is the sum of the direct beam radiation on the collector G_{bt} and the diffuse radiation on the collector G_{dt} [8, p. 26]. The intensity of the direct beam radiation on a tilted plane G_{bt} varies with θ as seen in Figure 2.
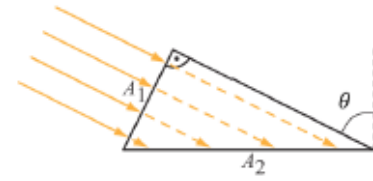

Figure 2: Intensity of beam irradiance on a plane with an angle of θ between the plane and the sun beams [8, p. 25]

$$G_{bt} = G_{bn} * \cos(\theta)$$

The diffuse radiation on the collector aperture G_{dt} is the sum of diffuse irradiation from the sky G_{st} on the collector and the radiation reflected from the ground and other objects G_{rt} on the collector [8, p. 26].

$$G_{dt} = G_{st} + G_{rt}$$

To calculate G_{st} and G_{rt} the following equations are used [8, p. 25/26] and as mentioned above the radiation on a tilted plane G_t can be specified with these values.

$$G_{st} = G_{dh} * 0.5 * (1 + \cos(\beta))$$

$$G_{rt} = \left((G_{dh} + G_b) * \frac{\rho_{grd}}{2}\right) * (1 - \cos(\beta))$$

$$G_t = G_{bt} + G_{dt}$$

4.3 Collector energy gain

On top of the reduction of the intensity of sun light there are other impacts caused by the design type of the collector that has to be included. The incident angle modifier (IAM) for the direct beam irradiance K_B and the IAM for the diffuse radiation K_d are both dependent on specific collector characteristics.

SolGain determines K_b dependent on an IAM at 50° from the test results of a given collector type [9, p. 19] for each hour of the year. However K_d is estimated once at the beginning of the simulation and used for each time step. The calculation follows the model of an isotropic sky [8, p. 173]. Simulation tools like Polysun and T*Sol ask the user to insert a value for K_d that is either self-defined or given in a collector test-sheet. To keep SolGain simple for unexperienced users it will calculate the IAM itself but leave the option open for researchers and students to enter more accurate IAM's.

A collector aperture's efficiency is distinguished by the collector efficiency, the conversion efficiency, its outlet temperature T_{out} and the usable energy output $\dot{Q}_{use}$ to a process. At first a temperature $T_{out,start}$ has to be determined by the program. Usually it is equal to the ambient temperature T_a of the current

time step. With it and the inlet temperature of the collector T_{in} a mean collector fluid temperature T_f is calculated which is needed to get the energy gaining of the aperture area $\dot{q}_{gain}$ [8, p. 67f]

$$T_f = \frac{T_{out,start} + T_{in}}{2}$$

$$\dot{q}_{gain} = \eta_0 * (K_b(\theta_l, \theta_t) * G_{bt} + K_d * G_{dt}) - c_1 * (T_f - T_a) - c_2 * (T_f - T_a)^2$$

This formula corresponds to the standard expression of full instantaneous steady-state efficiency test results in the latest standard [10, p. 105]. With the obtained data a new T_{out} can be calculated with the following equation [8, p. 69].

$$T_{out} = \frac{\dot{m} * \bar{c}_{p.fl} * T_{in} - \frac{c_{eff}}{2\Delta t} * T_{in} + \dot{q}_{gain} + \frac{c_{eff}}{\Delta t} * T_f(t - \Delta t)}{\dot{m} * \bar{c}_{p.fl} + \frac{c_{eff}}{2\Delta t}}$$

Herein $\dot{m}$ is the specific mass flow rate per m² aperture area which results from user input data and $\bar{c}_{p,fl}$ is the mean specific heat capacity of the collector fluid that will be set according to a default fluid suitable for the temperatures needed. The heat capacity of the collector c_{eff} is given with the heat loss coefficient of the first order c_1 and second order c_2 in a collector test report. SolGain will contain these data for a not yet defined selection of collector types. A time step Δt is always one hour and $T_f(t - \Delta t)$ stands for the mean collector fluid temperature of the last time step.

This part of the simulation is a loop that has to be repeated until the difference between $T_{out,start}$ and T_{out} is smaller than a defined value. The received T_{out} will be the new $T_{out,start}$ of the next loop.

At the current state of development T_{in} is constant for the whole process, but that can be adapted once complete heat cycles are included and therefore deliver more accurate results. In the future SolGain should be able to calculate system losses of pipes and heat exchanger as well as heat storage tanks for various process integration points inspired by the Integration Guideline [11].

5. Collector Output Comparison and Discussion

For the evaluation of the results three simulations have been made. Two of these compare the irradiation on the collector aperture and the energy supplied to the system with weather data from Durban, South Africa to a simulation run with Polysun. The other run was made with weather data from Graz, Austria and compares only the irradiation on the collector area to a simulation with TRNSYS. In the current phase of the tool development the annual and monthly values are examined rather than daily outputs.

5.1 Irradiation Comparison with TRNSYS

Figure 3 shows the irradiation on a flat plate collector (FPC) area of 200 m² in Graz as calculated in SolGain and TRNSYS with the same hourly horizontal irradiation data.
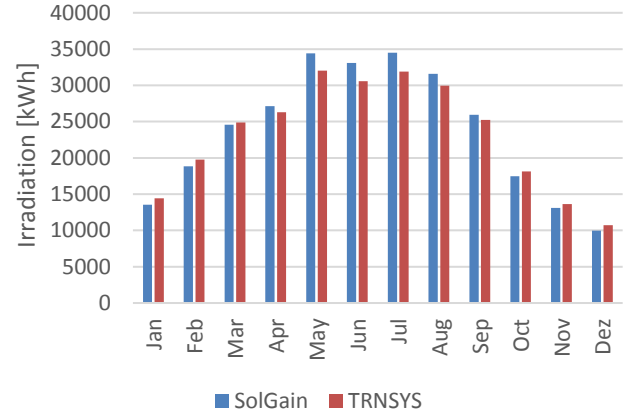

Figure 3: Calculated irradiation on 200 m² flat plate collector area in Graz with weather data from 2005, comparison of SolGain and TRNSYS

The annual sum of G_t is 284.2 MWh from SolGain and 277.6 MWh from TRNSYS. This corresponds to a deviation of 2 %, though the deviations for G_{bt} and G_{dt} are higher. The calculated G_{bt} on the collector area in SolGain is 11 % higher than the direct radiation in TRNSYS and G_{dt} in SolGain is 8 % lower than the diffuse radiation in TRNSYS. The reason for these significant differences might be an alternate definition of G_{bt} and G_{dt}, where some parts of the global radiation are considered as direct radiation in TRNSYS rather than diffuse radiation, since the overall deviation is relatively small. Another reason for variances is the exact position of the sun. SolGain doesn't take the longitude into account even though it has a small impact on the sun position and thus on the angle of the beam irradiation onto a tilted plane. An adaption at this point would lead to an unnecessary complication. As soon as heat storage tanks are included in SolGain, TRNSYS will be used for more evaluations.

5.2 Comparison with Polysun

To verify the calculation of solar thermal energy gains with SolGain, the outputs are compared with those of a Polysun simulation with the same inputs except for the weather data. Figure 4 shows the calculated irradiation on the collector area G_t in Durban, South Africa with weather data from 2015 in SolGain and with unknown weather data in Polysun on a flat plate collector (FPC) area of 5 m² aperture size.
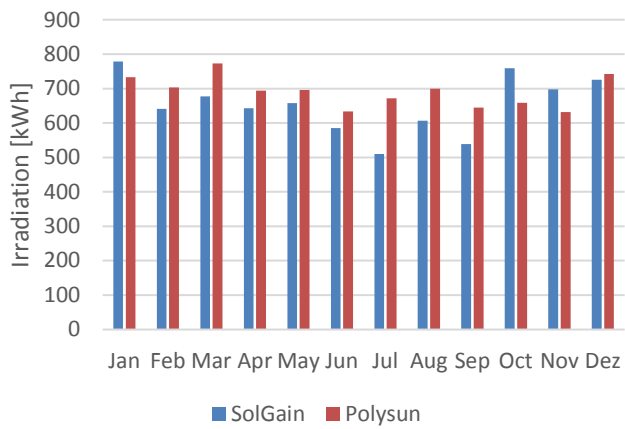
Figure 4: Calculated irradiation on 4.5 m² flat plate collector absorber area in Durban, comparison of SolGain and Polysun

The total deviation is 6% for the year. SolGain estimates an annual irradiation of 7,821 kWh and Polysun gives 8,284 kWh. It is clearly to recognize that there is a difference for every month. The main source for this inaccuracy might be the different source of weather data. For the SolGain simulations the weather data was collected from the SAURAN webpage [12], while the Polysun data might come from another origin and another year. For example the average temperature of the Polysun year (20.9 °C) was 0.4 °C lower than the temperature of the SolGain year (21.3 °C).

Same reasons apply for the differences in the next three graphics since the calculation of the energy output is directly dependent on the irradiation. The process scheme which is simulated for the FPC and the ETC is shown in Figure 5 with an inlet temperature of the process $T_{in,p}$ of 105 °C and an outlet temperature $T_{out,p}$ of 95 °C.
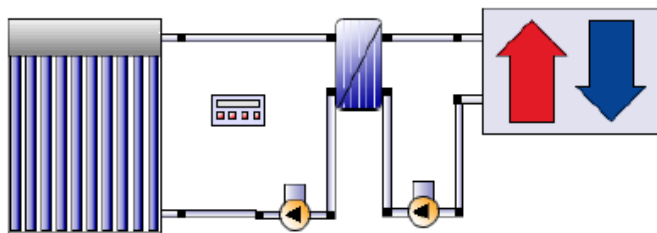

Figure 5: Simulated system in Polysun [1] with a static energy demand, pipe length are 1 m

The heat demand is static with a mass flow of 225 kg/h for the process heat circle. Heat losses of the heat exchanger and the pipes with 1 m length are neglected in the SolGain simulation. Translated into SolGain this implies a mass flow of 225 kg/h in the collector heat circle with a collector outlet temperature of 110 °C, which considers the efficiency of the heat exchanger. Since the process is unable to use more than the needed 110 °C

the energy given to the system is calculated with this temperature even though the actual outlet temperature of the collector is higher. This means, that the actual energy gain is higher than the solar thermal energy give to the system, which is displayed in Figure 6.
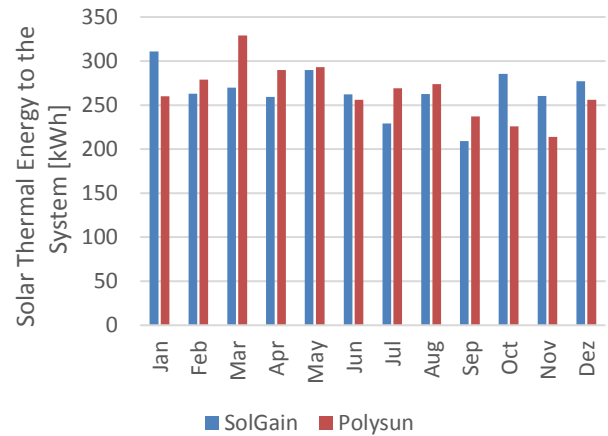

Figure 6: Calculated solar thermal energy to the system by 5m² of flat plate collector aperture, comparison of Solgain and Polysun

SolGain determines annual solar thermal energy gains of 3,179 kWh and Polysun 3,185 kWh. The annual deviation is only 0.19 % but significant in selected months. Especially March, July and October to January show big differences of up to 26 % in October. But since the source of weather data is as mentioned not the same, those inaccuracies are in the current state of the tool still acceptable.

Another simulation was made with an evacuated tube collector (ETC) of 5 m² aperture size but same heat sink and weather data. The results are shown in Figure 7 and 8.
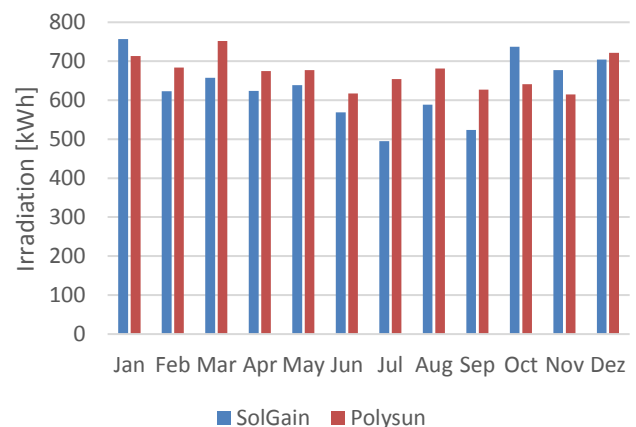

Figure 7: Calculated irradiation on 4.37 m² evacuated tube collector absorber area in Durban, comparison of SolGain and Polysun
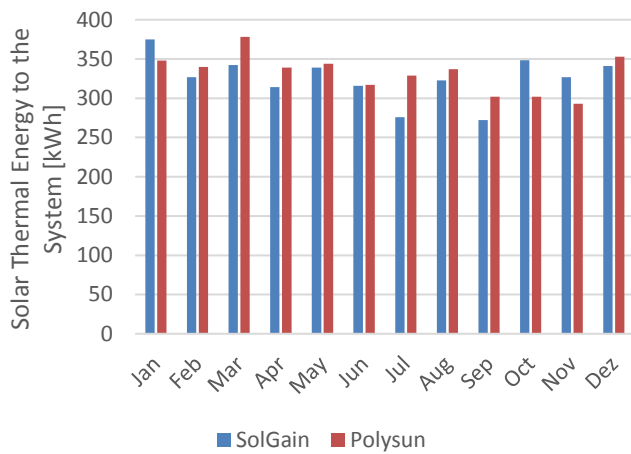
Figure 8: Calculated solar thermal energy to the system by 5m² of evacuated tube collector aperture, comparison of SolGain and Polysun

The irradiation on the ETC shows the same 6 % deviation as for the calculation with the FPC. SolGain achieves a total of 7,595 kWh and Polysun an annual sum of 8,058 kWh. The irradiation isn't the same as those for the FPC because the absorber area of the FPC is with 4.5 m² slightly bigger than the absorber area of the ETC with 4.37 m². The total energy supplied for the system is 3,901 kWh in SolGain and 3,983 kWh in Polysun. The deviation is 2 % and thus satisfactory. In both cases the solar thermal energy gain per kWh of irradiation in SolGain is higher the energy gain per kWh irradiation in Polysun. This might be caused by a different distribution of beam and diffuse radiation but also by different collector gain calculations or heat losses of the pipes and the heat exchanger that are not yet considered in SolGain. This has to be clarified during the next steps.

6. Conclusions and Next Steps

The results are promising and justify a further development of the tool. In SolGain, an annual collector output calculation in its current state consumes only seconds, which attributes to its simplicity. Still the output is close to the annual output of more complex programs and will therefore make no false promises to interested users. It will be exciting to see how future simulation test will run with equal weather data and additional components like pipes and heat exchangers with heat losses as well as heat storage tanks for various integration points of solar thermal heat. Therefore more extensive evaluation tests have to be made for the energy gaining of different collector types and more unordinary locations.

As a next step a valuable model of a heat exchanger and heat losses of pipes will be implemented to receive temperature feedbacks for the important points of the collector heat circle, e.g. heat exchanger inlet and outlet temperature and a more sustainable inlet temperature for the collector. So far the inlet temperature of the collector is static.

Nomenclature

Term	Meaning
c_1	First order heat loss coefficient
c_2	Second order heat loss coefficient
c_{eff}	Effective collector heat capacity
d_{local}	Current day
EQ	Day of Equinox
h_{local}	Current hour
G_b	Beam radiation on horizontal
G_{bn}	Direct normal radiation
G_{bt}	Beam radiation on tilted surface
G_{dh}	Diffuse radiation on horizontal
G_{dt}	Diffuse radiation on tilted surface
G_{rt}	Ground reflected radiation on tilted surface
G_{st}	Sky diffuse radiation on tilted surface
G_t	Total radiation on tilted surface
K_b	Incidence Angle Modifier for beam radiation
K_d	Incidence Angle Modifier for diffuse radiation
$\dot{m}$	Specific mass flow rate
$\dot{q}_{gain}$	Collector gain
T_a	Ambient temperature
T_f	Mean fluid temperature in the collector
T_{in}	Collector inlet temperature
$T_{out,start}$	Collector outlet temperature at iteration start
T_{out}	Collector outlet temperature at iteration end
t	Current time step
Δt	Width of a time step (one hour)
β	Tilt of the collector
γ	Orientation of the collector
δ	Declination of the sun
θ	Angle of Incidence on the collector
θ_s	Zenith angle of the sun
φ	Latitude
ω	Hour angle of the sun
η_0	Collector conversion factor
ϕ_s	Azimuth angle of the sun

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