Overview and description of simulation tools for solar industrial process heat systems

Deliverable C2

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Contents

1 IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.*

The members of the IEA SHC collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings. A total of 57 such projects have been initiated, 47 of which have been completed. Research topics include:

- ⚖ Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- ⚖ Solar Cooling (Tasks 25, 38, 48, 53)
- ⚖ Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- ⚖ Solar District Heating (Tasks 7, 45, 55)
- ⚖ Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56)
- ⚖ Solar Thermal & PV (Tasks 16, 35)
- ⚖ Daylighting/Lighting (Tasks 21, 31, 50)
- ⚖ Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- ⚖ Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- ⚖ Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- ⚖ Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:
- ➢ SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- ➢ Solar Heat Worldwide – annual statistics publication
- ➢ Memorandum of Understanding – working agreement with solar thermal trade organizations
- ➢ Workshops and seminars

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2   Introduction

Solar Heat for Industrial Processes (SHIP) is currently at the early stages of development. Less than 160 operating solar thermal systems for process heat are reported worldwide (as of 2015), with a total capacity of about 100 MW$_{th}$ (140,600 m²). Many of these systems are of experimental nature, and are relatively small scale. On the other side large plants with several thousand square-meters field size exist. This indicates that there is a great potential for market and technological developments expected, as for example 28% of the overall energy demand in the EU27 countries originates in the industrial sector, majority of this is heat of below 250°C.

Whereas most solar thermal process heat projects work with non-concentrating collectors, in the last years also a number of concentrating collectors are being devloped. With these higher temperatures can be achieved. Therefore especially in countries with high DNI radiation often the question arises whether a concentrating collector or a non-concentrating collector should be used.

Integration of solar heat can be done on the process level, but also on the supply level. All these different approaches to solar process heat should be analysed easily by simulation. However up to now the limitations of individual programs with respect to all technologies and integration possibilities were not known. A comparison study with defined reference cases has been performed within Task 49 in Subtask C2.

Within this document a short description of simulation tools used for the comparison of case studies [1] will be given. The document does not aim at a complete description of the tools with all its mathematical, numerical and modelling details, it only intends to identify the main features and characteristics of tools which may affect the modelling of solar process heat case studies and their results. All the tools have been used at least in some of the case studies and results are being analyzed in a different document. [2-5]. It is based also in a survey of simulation tools performed at the beginning of IEA Task 49.

3   Description of Simulation Tools

3.1   TRNSYS (ISE/W. Platzer)

3.1.1 Introduction

TRNSYS is a transient systems simulation program with a modular structure. It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. The modular nature of TRNSYS gives the program tremendous flexibility, and facilitates the addition to the program of mathematical models not included in the standard TRNSYS library. TRNSYS is well suited to detailed analyses of any system whose behaviour is dependent on the passage of time. TRNSYS has become reference software for researchers and engineers around the world. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells. In our simulation Version 17.1 was used.

3.1.2 Mathematical background and Programming

TRNSYS is an acronym for a "transient simulation program" and is a quasi-steady simulation model [TRNSYS, 1996]. The program consists of many subroutines that model subsystem components. The mathematical models for the subsystem components are given in terms of their ordinary differential or algebraic equations. With a program such as TRNSYS, which has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output, the entire problem of system simulation reduces to a problem of identifying all the components that comprise the particular system and formulating a general mathematical description of each.

Once all the components of the system have been identified and a mathematical description of each component is available, it is necessary to construct an information-flow diagram for the system. The purpose of the information flow diagram is to facilitate identification of the components and the flow of information between them. Each component is represented as a box, which requires a number of constant PARAMETERS and time dependent INPUTS and produces time dependent OUTPUTS. An information flow diagram shows the manner in which all system components are interconnected. A given OUTPUT may be used as an INPUT to any number of other components.

3.1.3 Modelling of solar thermal system

3.1.3.1   Collector model(s)

The collector model used in the TRNSYS simulations was the dynamical collector model TYPE 832 (V3.07). The model was used with the collector parameters given in the case description with optical efficiency h0, with thermal loss parameters a1 and a2 as well as a one or twodimensional incidence angle modifier where angular values

were read in, the basic equation being:

$$\dot{q}_{out} = \eta_0 \cdot (K_b \cdot I_b + K_d \cdot I_d) - a_1 \cdot (\vartheta_{mf} - \vartheta_{amb}) - a_2 \cdot (\vartheta_{mf} - \vartheta_{amb})^2 - C_{eff} \cdot \frac{d\vartheta_{mf}}{dt}$$

The determination of the actual heat gain and collector output is an iterative process in this model. In a first step, the actual collector heat gain with the inclusion of the temperature dependent thermal losses of the collector are calculated, and in a second step, the outlet temperature of the collector ϑ_{out} of this time step is calculated from the collector gain q_{gain}.

3.1.3.2   Storage Model(s)

For the tank a multiport stratified water storage model with 2 inlets and 2 outlets was taken (TYPE 342V1.99F).

3.1.3.3   List of other used components

Other components radiation processor, heat exchanger, etc. were used in the modular description of the solar system. For the evaporation an equation was used.
For the demand profile numerical values were given for different hours within the year, depending on weekday and week in the year
Controllers sent signals to pumps, diverters and mixers as hydraulic elements, controlling thus the mass flow through individual pipes depending on the given control logic.
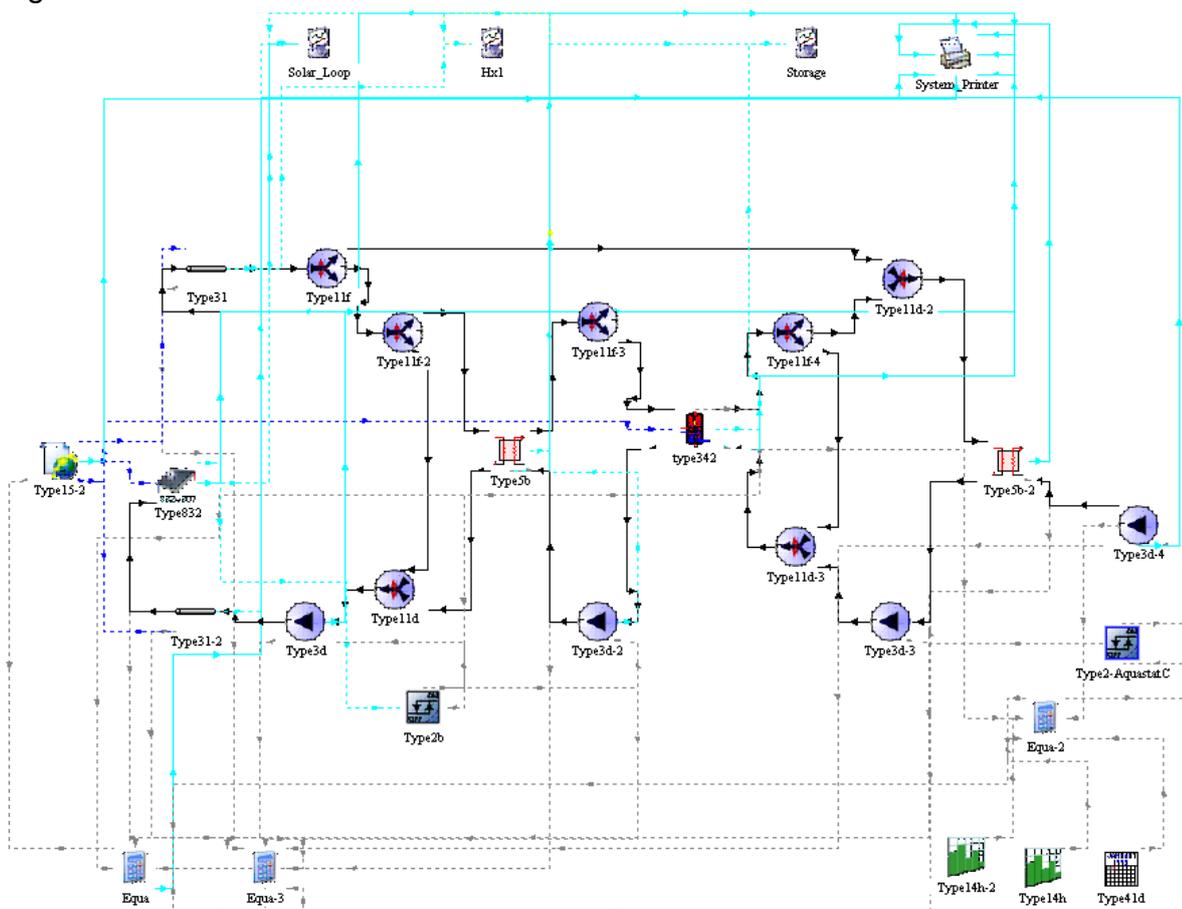

Figure 1: Typical TRNSYS deck showing the interconnections of the different TYPEs (Example Case 3)

The evaporator equations are shown in the following:

Mfr_oil_out = Mfr_oil_in

T_oil_out = 250

Q_oil = Mfr_oil_in*(1/3600)*2*(T_oil_in-T_oil_out)

T_st_sat = 244.18

Mfr_st = 159

Q_st_sat_low = Mfr_st*(1/3600)*4.2*(T_st_sat-T_st_in)

Q_st_sat_high = Q_st_sat_low+Mfr_st*2260*(1/3600)

T_st_in = 103

T_st_out   = LT(Q_oil,Q_st_sat_low)*(T_st_in+Q_oil/(4.2*Mfr_st))+LT(Q_oil,Q_st_sat_high)*GE(Q_oil,Q_st_sat_low)*T_st_sat+GE(Q_oil,Q_st_sat_high)*(T_st_sat+(Q_oil-Q_st_sat_high)/(4.2*Mfr_st*(1/3600)))

DT_oil = T_oil_in-T_oil_out

Q_steam_demand = 127*Load

Q_col_out = Q_col/3600

Q_conv_diff = Q_steam_demand-Q_oil

DT_steam = T_st_out-250

Steam_quality = GT(Q_oil,Q_st_sat_low)*(Q_oil-Q_st_sat_low)/(Q_st_sat_high-Q_st_sat_low)

The evaporator calculated the amount of steam produced from a certain heat amount extracted from the oil-loop with prescribed mass flow. If the temperature of the oil is high enough also superheating can be calculated assuming for water and steam a constant heat capacity of 4.2 kJ/(kg*K).

3.1.4 Case Studies

3.1.4.1   Integration approach

In all the studies the hourly demand profile required a certain temperature and had a fixed return temperature. The required mass flow at each hour thus could be calculated using a constant heat capacity of the fluid and the heat needed. This mass flow was prescribed. The heat supplied by the solar system at a given time was calculated by the mass flow and the difference between supply from the heat exchanger and the return flow of the process. The remaining heat was assumed to be supplied by the conventional source.

3.1.4.2   Flexibility and freedom of system design (1/2)

TRNSYS is very flexible as it allows multiple choices of models for collectors, storage tanks, controllers etc. Therefore just by choosing different models for the same case one might end up with producing different results. Especially the stratification properties of the water storage tanks influence the results quite substantially. And for this model the number of nodes, the parameters describing the heat exchange between layers are important. TRNSYS is thus less practical when rather general studies are the objective. Whenever detailed system descriptions with well-described components are available where model parameters are clearly defined for a specific component model from testing results, then this program should be chosen.

3.1.4.3   Problems and work arounds (in Case Studies

The TRNSYS deck does not provide a possibility to actually model evaporation as a two-phase process. Using the equation tool only one is able to calculate the evaporated water using a fixed evaporation enthalpy for a given temperature.

3.1.4.4   Limitations (in Case Studies)

The simulation of air collectors is possible in principle by changing the physical properties of the collector fluid, however due to resource limitations a process heat system with a working non-standard air collector type was not simulated.

3.1.5 Summary

TRNSYS is a very flexible and hence sometime ambiguous tool to be used. The results will depend to some extent on models and parameters to be chosen by the simulator.

3.1.6 Literature

TRNSYS1996   TRNSYS program manual. Madison (USA): Solar Energy Laboratory, University of Wisconsin; 1996.

3.2 Colsim (ISE/A. Helmke)

ColSim is a simulation software initially designed and further developed at Fraunhofer ISE to perform calculations for solar thermal systems. ColSim can perform quasi-dynamic hydraulic simulations and allows for the integration of complex control strategies.

3.2.1 Introduction

The original aim of the development was testing of controllers for solar collectors and development of a simulation environment with small time steps and short computation time for annual analysis of dynamic systems. ColSim is programmed in ANSI C, has the public domain status and uses the freely available tools "xfig" as graphical interface and "Gnuplotter" for visualization. The software is similar to the simulation environment TRNSYS, modular in structure.

3.2.2 Mathematical background and Programming

The solver algorithm used in ColSim is an explicit modified one-step - Euler method. In the hydraulic circuit starts and ends with the initial pump. The computation sequence starts with the initial pump and follows the hydraulic arrangement and successively computes the other components in subsequent time steps. To ensure sufficient stability in the Euler method, the calculation steps must be accordingly small. The initial pump generates a "Plug", which is a mass of liquid circulating into the system. Following the hydraulic circuit, the output of the pump becomes the input of the next type connected. The properties of the plug are changed according to the code of the type itself. In ColSim input and output mass flow must be equal, so mass cannot be accumulated in a type. This approach requires that every loop into the ColSim build is a closed loop and that all the boundaries conditions are well defined.

The fluid state in a flow-through system can be characterized by the following variables: temperature, pressure, enthalpy, title of vapor and velocity.

The spatial and temporal evolution of the fluid state can be described by different balance equations such as: balance of mass, momentum and energy.
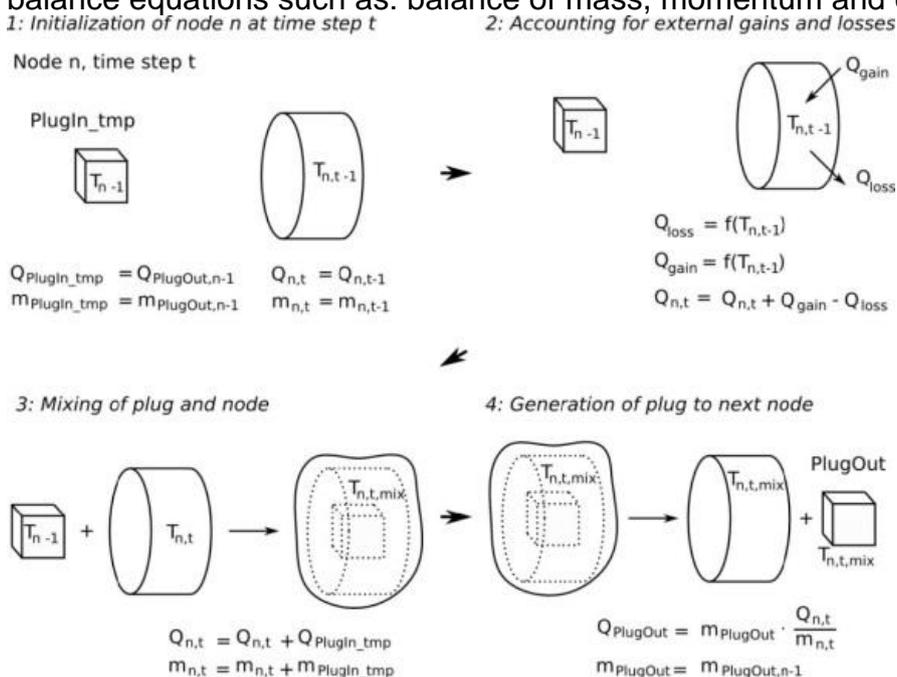

Figure 2: Plug flow model ColSim

3.2.3 Modelling of solar thermal system

3.2.3.1   Collector model(s)

Stationary Collector model (Flat plate collector, evacuated tube collector etc)

In the ColSim type firstly the solar energy gains are calculated, as shown in the following equation:

$$Q_{sun} = \eta_0 * A * \left(K_{\tau\alpha,dir} * G_{bt} + K_{\tau\alpha,diff} * G_{dt} \right)$$

Q_{sun} is the energy absorbed by the collector, not considering the thermal losses. η_0 is the optical efficiency is calculated with a null incidence angle, $K_{\tau\alpha,dir}$ and $K_{\tau\alpha,diff}$ are the incidence angle modifiers for direct, respectively diffuse radiation, G_{bt} and G_{dt} are the beam and diffuse radiation on the tilted surface. The incidence angles $K_{\tau\alpha,dir}$ and $K_{\tau\alpha,diff}$ are read by the model from an external file.
Then the thermal losses are calculated, as shown in equation:

$$Q_{,loss} = [\, a_0 * (T_{mean} - T_{amb}) + a_1 * (T_{mean} - T_{amb})^2] * A_c$$

a_0 and a_1, as well as η_0, are parameters to characterize the collector.
The collector gain is then calculated as $Q_{sun} - Q_{loss}$; this term is then divided for the number of nodes in which the collector is discretized and is used as Q_{gain} in the Plug Flow model shown in Figure 2.
Linear concentrating collector (Parabolic through collector, linear Fresnel collector etc)
Model for The solar energy absorbed by the collector is calculated as in equation

$$Q_{sun} = \eta_0 * A * K_{\tau\alpha} * G_{bt}$$

Where G_{bt} is the direct irradiation on the collector aperture area. The incident angle coefficients are read from an external IAM file.
Energy losses are subtracted from the absorbed energy to calculate the collector gain. In linear focused collector fields the so-called end losses must be considered: end losses are energy losses related to the irradiation of solar rays reflected by the end of the mirror line, missing the absorber.
Heat losses are calculated in the stationary model; the solar energy gain is then calculated subtracting the end losses and heat losses to the absorbed energy.

Once through model for direct steam generation
This type allows to set a target temperature for the medium at the collector outlet. by the fluid at the outlet. The conditions in the collector tube are assumed to be ideal and the steam properties are taken from an external fluid library.
If the outlet and inlet conditions of the fluid are known, as well as the gained energy, the solar loop pump can be controlled to achieve saturated steam at the collector outlet.
If the solar energy gained is more than the energy required by the steam network, the

mass flow that can be generated by the solar field is bigger than the entire feed water mass flow. In order to avoid superheating the mirrors are defocused, limiting the maximal power of the solar field.

3.2.3.2   Storage Model(s)

As shown in Figure 3, the storage type is modelled discretizing a volume in n horizontal layers, each at a uniform temperature. For each of them an enthalpy balance is calculated. This energy balance takes in account several heat transfer mechanism, such as inlet and outlet mass flows, effects of internal heat exchangers, as well as convection and conduction between consecutive layers and heat losses to the environment. The results of the calculation are the temperature of the nodes, the outlet temperature of the flows and the heat losses.
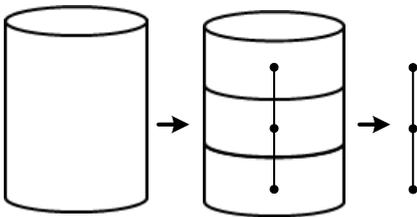
Figure 3: Storage discretization

<u>Components</u>

- Pump

- Pipes

- Throttle

- Flow diverter/ mixer (used for mixing valve purposes)

- Heat exchanger (counter flow model with fixed UA value) used also as evaporator

- Heater / Cooler to simulate a boiler or a load

- Controllers

3.2.3.3   List of other used components

ColSim contains standard components for weather data generation from standard waether input data, output generators which have been used.

3.2.4 Case Studies

3.2.4.1   Integration approach

In the studies the demand profile was modelled with much shorter time steps and subhourly resolution. It required a certain temperature and had a fixed return temperature. The required mass flow at each hour thus could be calculated using a constant heat capacity of the fluid and the heat needed. This mass flow was prescribed. The heat supplied by the solar system at a given time was calculated by the mass flow and the difference between supply from the heat exchanger and the return flow of the process. The remaining heat was assumed to be supplied by the

conventional source.

3.2.4.2 Flexibility and freedom of system design

COLSIM is very flexible as it allows to use different models for collectors or even to adapt the models if needed, as source code is availbale, Especially on the control side more options would exist, as the program is written especially for optimizing control issues in short time-steps. This means also that the description as availbale does not uniquely define the case as different models could be choses where one might end up with different results. However this was investigated systematically. Obviously the case study was meant only to be on the level of a prefeasibility conceptual study.

Of course also assumed stratification in the water storage tanks influence the results. COLSIM is thus less practical when basic studies on a low detailing level are the objective. It is more suitable for optimizing operational parameters of an existing plant or of a plant with detailed planning – cases where other models probably have restrictions to resolve the details..

3.2.4.3 Problems and work arounds

No actual work arounds have been used in the study. However of course the collector model with direct steam generation uses a simplified approach based on local enthalpy. balances and empirical heat transfer coefficient functions for the steam-wall heat transfer, not really a numerical fluid dynamics simulation.

3.2.4.4 Limitations

The simulation of air collectors should be possible in principle but has not been developed yet. So due to resource limitations a process heat system with a working non-standard air collector type was not simulated.

3.2.5 Summary

COLSIM is an advanced scientific tool providing many features which were not relevant for this simplified case studies. The results depend to some extent on models and parameters chosen by the simulator.

3.3   Insel (ZAFH/I. Ben Hassine)

The following tool description is partly extracted from the Insel 8 Tutorial. Insel is a trademark of the doppelintegral GmbH.

3.3.1   Introduction

INSEL is an acronym for INtegrated Simulation Environment Language. INSEL provides an integrated environment and a graphical programming language for the creation of simulation applications. INSEL was originally developed for modeling of renewable energy systems, the first versions being written at the former Renewable Energy Group at the Faculty of Physics of Oldenburg University, Germany. Insel provides graphical symbols that can be interconnected by mouse operations to build up larger structures. The graphical symbols can represent mathematical functions, real components like solar thermal collectors, photovoltaic modules, wind turbines and batteries, for example, or even complete technical systems of any kind. The graphical elements of INSEL are blocks.

3.3.2   Mathematical background and Programming

The core component of INSEL is the inselEngine which is a full compiler that can interpret and execute applications written in the INSEL language or created from the graphical pre-processor VSEit. insel 8 provides an import function for INSEL 7 models written in HP VEE. Different libraries are provided in Insel. For example Energy meteorology and data handling are available as library inselEM. This library contains algorithms, like the calculation of the position of the Sun, spectral distribution of sunlight, radiation outside atmosphere. A programmable environment with a user-written library inselUB is also available. Practically all fields of engineering applications can be built in a very structured way in it. All standard programming languages like Fortran, C/C++, which can be compiled into object code, are supported.

3.3.3   Modelling of solar thermal system

3.3.3.1   Collector model(s)

The collector model used in the simulation case 1 is based on the test method under quasi-dynamic conditions according to EN12975-2. The collector useful heat is defined as:

$$Q = F'(\tau\alpha)_{en}K_{\theta b}(\theta)G_b + F'(\tau\alpha)_{en}K_{\theta d}G_d - c_6 uG$$
$$- c_1(t_m - t_a)^2 - c_2(t_m - t_a) - c_3 u(t_m - t_a)$$
$$+ c_4(E_L - \sigma T_a^4) - c_5 \, dt_m/d\tau$$

where

c_1	heat loss coefficient at $(t_m - t_a) = 0$ is modelled as $F'U_0$ [W/(m^2 K)],
c_2	temperature dependence of the heat losses, equal to $F'U_1$ [W/(m^2 K^2)],
c_3	wind speed dependence of the heat losses, equal to $F'U_u$ [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 zero loss efficiency, a collector constant [s/m],

The Influence of the angle of incidence on the optical performance of the collector: Incidence Angle Modifier (IAM) is taken into account.

3.3.3.2   Storage Model(s)

Two types of storage tanks are available in the Thermal energy - Tanks category, a fully mixed (block TANKFM) and a stratified storage tank (block TANKST). Both tank models can be used for heat and cold storage as well. The characteristics of the storage tanks with respect to their size and heat losses stratified are described by six parameters in case of the fully mixed tank. In case of the stratified storage tank two more parameters are necessary to define the effective vertical heat conductivity and the number of nodes N, in which the storage volume shall be divided. The maximum number of nodes is limited to 200. However, in normal cases, depending on the storage size, 5 to 20 nodes are sufficient for nearly all calculations.

3.3.3.3   List of other used components

- Heat exchanger

- Pipe

- Hysteresis controller

Insel contains other component models.

3.3.4 Case Studies

3.3.4.1   Integration approach

Graphical programming languages like INSEL use a different approach than algorithmic programming languages like Fortran or C. Instead of statements, these languages provide graphical symbols, which can be interconnected by mouse operations to build up larger structures. The graphical symbols can represent mathematical functions, real components like solar thermal collectors, photovoltaic modules, wind turbines and batteries, for example, or even complete technical systems of any kind. The graphical elements of INSEL are blocks. It is possible to model every solarthermal system by connecting the inputs and outputs of the different blocks. In the following example an evacuated solar collector and the stratified storage tank are connected in two different ways. In the first one, the evacuated solar collector directly connected to the storage tank. In the second case, a counter flow heat exchanger from Thermal - Heat exchangers – Simple heat exchangers- is integrated with the default parameters between the evacuated collector and the stratified storage tank. The energy content of the storage tank for both cases is plotted in one graph for a time period of 36 000 s with a time step of 20 s. A solar irradiation on the collector

plane of 900 W/m² and an ambient temperature of 20°C are applied. For this example it is necessary to connect the output temperature of the storage tank and/or the heat exchanger to the input temperature of the collector/heat exchanger. However, at calculation start the output temperatures of the components are not known, therefore DELAY blocks form Math - Loops have to be integrated between the outputs and the inputs. A DELAY block always outputs the calculated value of the previous time step. Therefore, an initial value has to be defined as parameter, to provide an output value for the first calculation time step.
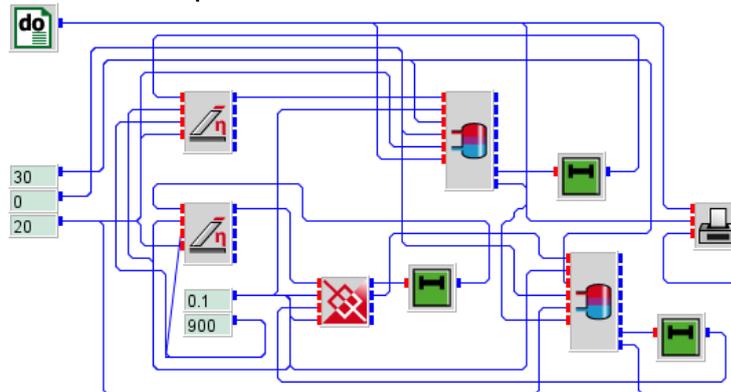
Fig. 1 Block connections in Insel

3.3.4.2 Flexibility and freedom of system design

Different system configurations can be modeled by connecting the component blocks. Newer user blocks (e.g. for customized control) can be programmed in C+ or Fortran and added to the inselUB library.

3.3.4.3 Problems and work arounds (in Case Studies

The usage of DELAY blocks may influence the functionality of some control blocks. The dead time of the controlled system –and therefore the number of the DELAY blocks- should be hold as low as possible to guarantee good controllability.

Some blocks (like the storage and the pipe types) require a short step time (seconds to minutes) to properly calculate the temperature course. A tradeoff between simulation time and result accuracy has to be made.

3.3.4.4 Limitations (in Case Studies)

Not yet.

3.4 TSOL (AEE INTEC/F. Mauthner)

Information about the software T*SOL® was kindly provided by and discussed with DI Uwe Radke, software engineer at Valentin Software GmbH.

3.4.1 Introduction

T*SOL® is a simulation program that allows to accurately calculate the yield of a solar thermal system dynamically over the annual cycle. With T*SOL® one can optimally design solar thermal systems, dimension collector arrays and storage tanks, and calculate the economic efficiency. T*SOL® offers around 200 preconfigured systems and extensive automatic design assistance. The dynamic annual simulation calculates temperatures and energy values in intervals of one to six minutes (default: hourly time steps). System parameters such as efficiency and solar fraction are calculated from the simulation results.

In addition to the preconfigured systems, T*SOL® comes with an up-to-date database of over 2,500 flat-plate and evacuated tube collectors, 700 storage tanks and 1,100 boilers and auxiliary heaters.

The MeteoSyn climate database contains around 8,000 global data sets, based on Meteonorm 7.0 with the averaging period 1986-2005, which can be easily selected via an interactive map. New climate data can be created either by interpolation from existing measured values or on the basis of given monthly mean values.

3.4.2 Mathematical background and Programming

Systems in T*SOL® consist of single components (e.g. collectors, tanks, boilers). All these components are represented by physical models which have to deliver precise results in a reasonable simulation time. This is realized by simulation time intervals of one to six minutes. Assumptions which do not affect the results considerably but reduce simulation time (e.g. constant heat capacities) are taken. Each simulation interval is calculated using linear equations and in addition in some cases iterations or other mathematical and numerical methods are used. The results are verified by energy balances. In order to guarantee constant and consistent simulation results each modification of existing physical models or the implementation of new physical models is documented and automatic regression tests are outperformed.

For the implementation of the physical models integrated development environments like Delphi and Visual Studio and modern programming languages (e.g. C#) and databases (SQL CE) are used.

3.4.3 Modeling of solar thermal system

3.4.3.1 Collector model(s)

Multiple collectors are combined in collector arrays that are either connected to tanks directly or via heat exchangers. The irradiation is the sum of direct and diffuse radiation minus shading. For the different collector types (flat plate, concentrating) the angle modifiers for direct and diffuse irradiation are needed. The solar yield is diminished by thermal and optical collector losses.

While simulation the collector is split into three sections. For each sector an energy balance based on a differential equation that includes losses, the water flow and the heat capacity is calculated. All needed parameters for commercially available

collectors are gathered from test certificates, e.g. the linear and quadratic coefficients for thermal losses.

3.4.3.2 Storage Model(s)

For the calculation of tank temperatures the water content is split into a variable number of layers with a constant temperature. New layers are generated due to inflowing water (from collectors, boilers, circulation, etc.). Layers with a sufficient similar temperature are merged. Effects like rising warm water, losses over the surface and pipe connections and heat conduction between layers are taken into account. There are numerous fittings for the use in tanks, e.g. electric heating elements, internal heat exchangers or internal tanks (combination tanks). All heat exchange processes are calculated in counter-current mode. Thermal losses of the storage itself as well as of the piping connections are considered in the model.

3.4.3.3 List of other used components

Besides of collectors and tanks, solar loop piping, boilers, external heat exchangers and different kinds of heat demands (consumers) are simulated. Characteristic parameters for each component need to be defined by the user (e.g. length of solar loop piping and insulation characteristics, kA-value of heat exchangers, capacity and efficiency of boilers, etc.). All consumers (e.g. domestic hot water, space heating, swimming pool heating, process heat, etc.) are defined by a load profile with annual, weekly and hourly values for the energy demand (kWh) and by fixed supply and return temperatures.

Controllers are basically defined by means of (user-defined) sensor positions and temperature set-points (On/Off controllers). Pumps can be operated with or without speed control.

3.4.4 Case Studies

3.4.4.1 Integration approach

In the software version T*SOL$^{®}$ expert 4.5 (2014) four preconfigured systems especially for solar process heat simulations are available and other preconfigured systems may be adapted by the (experienced) user according to the case study. All four systems may be equipped with either flat plate or evacuated tube collectors with water or a water/glycol mixture as heat transfer medium. Three systems are equipped with solar energy storage tanks with either internal heat exchanger (A8) or external heat exchanger (A13, A14.1). The auxiliary heater is either pre-defined as continuous flow heater (A8, A14.1) or storage integrated (A13). System A15 is defined as a solar thermal system directly connected to a process heat sink (no storage). The process heat sink may be defined as a thermal energy demand on hourly bases with fixed supply and return temperatures only. Additional heat exchangers on process side as well as the process loop piping or the process loop pumps cannot be specified in the simulation.

A8
Space Heating Only System
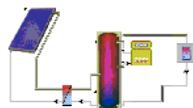
A13
Buffer Tank System with Process Heating
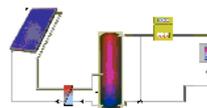
A14.1
Buffer Tank System with Process Heating a...

A15
Process Heating without Tank

3.4.4.2 Flexibility and freedom of system design (1/2)

Due to the number of preconfigured systems provided by the software, process heat

simulation models can be developed very quickly for a wide range of industrial cases. The components of the preconfigured systems (collector and collector field, collector loop piping, collector loop heat exchanger, storage tank, boiler, heat sink, control strategy) can be parameterized by the user.

By now the main limits of the software are linked to the process heat sink. In the version T*SOL® expert 4.5 (2014) only one heat sink can be calculated which is solely determined by the energy demand profile and fixed supply and return temperatures. Further on only liquid based flat plate and evacuated tube collectors are supported by the software which limits the field of application to pressurized hot water systems appropriate for the respective collector type used.

3.4.4.3 Problems and work arounds (in Case Studies

Due to temperature, heat transfer media and collector type constraints the simulation of the cases studies with the software T*SOL® expert 4.5 (2014) was limited to CASE 1 – Pre-Heating of Make-up Water, CASE 2 – Bath Heating and CASE 3 – Water Heating (Return Flow Temperature Lift).

Because simulations with T*SOL® are based on preconfigured systems special hydraulic set-ups (especially on process-side) could not be considered in the simulation (e.g. heat exchangers on process side). All other given boundary conditions (e.g. load profiles, climate data, collector characteristics, solar loop heat exchangers and piping, etc.) could be considered by the user.

3.4.4.4 Limitations (in Case Studies)

The existing process heat systems currently available in T*SOL® were the first step towards the integration of process heat to the simulation software. Today, the process heat consumption can only be defined for one heat sink and with given feed and return temperatures. There is no modeling of industrial processes like drying, galvanic baths, batch processes etc.

In one of the next versions of T*SOL® in 2015 the results of the research project SoProW will be published. The solar energy from the collector array can then be used for preheating or, in combination with an additional boiler, as supply stream. Both types come in combination with or without a buffer tank. So there will be four new systems available which integrate four types of consumers: space heating, heat exchanger, tank with internal heat exchanger, basins. Each consumer has its own set of parameters (temperatures, flows) and a profile for the operating times and up to four different heat sinks (one space heating + three processes) can be simulated simultaneously. Moreover T*SOL® will supply one additional system with steam and pressurized water up to 180 °C. These high temperatures will be delivered by the new collector types Fresnel and Parabolic Trough.

3.4.5 Summary

T*SOL® is a highly intuitive and (compared to other more complex simulation tools like e.g. TRNSYS) little time consuming simulation software for a wide range of solar thermal applications. The software bases on around 200 preconfigured solar thermal system concepts which allow the user to quickly adapt and parameterize hydraulic concepts for different applications (e.g. domestic hot water systems, solar combi systems, solar district heating and solar process heat applications). Today, the software supports water based systems with non-concentrating solar thermal collectors.

For the simulation of solar process heat applications T*SOL® provides a number of

applicable preconfigured systems which enable quick energy yield and economic simulations for a wide range of industrial applications such as pre-heating of make-up water or heating of closed process supply loops. Due to the preconfigured systems the modeling of complex hydraulic set-ups and corresponding control strategies (especially of the process side) is limited. Nevertheless in many cases any of the available preconfigured systems can be adapted and simplified according to the case investigated.

For 2015 a new release of T*SOL$^®$ is scheduled which enables a more flexible simulation of the process side. Different kinds of process heat consumers (space heating, heat exchanger, tank with internal heat exchanger, basins) will be available which may be defined by means of both temperatures and flows and up to four different heat sinks (one space heating + three processes) can be simulated at the same time. Moreover T*SOL$^®$ will supply one additional system with steam and pressurized hot water up to 180 °C in future and Fresnel as well as parabolic trough collector models will be implemented.

3.5   Polysun (SPF/ Jana Möllenkamp)

Information about the software Polysun® was kindly complemented by Andreas Witzig (Managing Director at *Vela Solaris*).

3.5.1   Introduction

Polysun® is a simulation program which allows designing solar thermal, heat pump and photovoltaic systems as well as combined systems dynamically. The reliable yield prediction includes the use of worldwide weather data and topologic shading. Polysun® is able to provide useful technical reports and necessary information for the application of subsidies. The software is available for Windows or Mac applications in 13 languages.

A designer can use and edit one of the preconfigured systems in Polysun® or create new systems by combining components such as storages, pumps, collectors and pipes. The capability of designing arbitrary hydraulic topologies is especially useful for process heat applications. The parameters (e.g. size, efficiency etc.) of each component can be modified individually. The component database comprises 4400 Solar Keymark collectors, 1160 collectors with Ashrae/SRCEE certificate and a small number of collectors according to the Chinese standards. Furthermore the database comprises 2000 storage tanks, 566 heat pumps, 60 co-generators, 40000 PV modules, 8000 inverters and other components.

The large template database offers **preconfigured systems** for residential systems, space heating/cooling, domestic hot water, pools, combined systems as well as commercial and industrial systems such as process and district heating. Building simulations are available with several buildings and multiple dwelling units. Furthermore, there are simulation models for cogenerators and combined heat and power systems.

The Polysun software comprises economic analysis. However, it is optimized for solar thermal heating systems and rooftop PV systems. Therefore, in process heat applications it is necessary to enhance the economic analysis by means of the Polysun® simulation results and special calculations, e.g. in Excel.

Yearly system parameters such as efficiency, solar fraction or auxiliary heat demand are calculated from the simulation results.

3.5.2   Mathematical background and Programming

Polysun® is a component-based simulation software written in the Java programming language. **A dynamical and physics-based simulation algorithm calculates electrical and thermal energy flows as well as hydraulic systems over the annual cycle.**   All components are implemented according to their physical behavior. If available, the models are chosen close to the international standards such as Solar Keymark for solar collectors or the DIN norms EN 255, EN 14511 and EN 14825 for heat pumps.

Depending on the input values of the system an optimized algorithm calculates the required time step (minimum one second) for solving energy and mass balances of the dynamic annual simulation accurately. Hourly output values are shown in table form or graphically. A "Developer" user level allows obtaining values for each time step.

A plug-flow algorithm is implemented pursuing time integration with the Euler method. A small time step is chosen which automatically adjusts to cover all switching events such as the start of a heater or a shutter action. Energy balance is guaranteed automatically by

choice of the physical model formulation.

While the physical models of the components are typically quite simple, the complex behavior of the system is represented in detail due to the controllers that appear on the drawing area and are editable by the user. A programmable controller is available since Polysun® version 6.0 in 2013, which is a key component for process heat applications.

3.5.3 Modelling of solar thermal system

Due to being component based Polysun® provides a large databank of components (e.g. pumps, storages etc.) which are available on the market with its physical properties either given by the suppliers or generated generally. The properties of the components can be modified partly or completely by the user.

3.5.3.1   Collector model(s)

Polysun® is able to simulate different types of collector from Flat Plate, Vacuum Tube/Flat Plate, CPC, Fresnel, Pararabolic Trough up to PVT collectors. The thermal and optical losses of the collectors are calculated by use of empirical determined physical properties which are taken from certificates of commercially available collectors. The exact axis orientation of the collector is defined by the user. Within a collector field the collectors are connected in parallel or serial. Different collector fields can differ in their orientation.

3.5.3.2   Storage Model(s)

The storage models in Polysun® differ in their size, type (e.g. internal, external, jacket heater) and properties (e.g. type, size and height) of the heat exchanger, stratification model and type of internal auxiliary heater.

The volume in the thermal storage is divided into 12 horizontal layers of the same temperature. Heat conduction between the layers and natural convection due to temperature differences are taken into account. Thermal losses are determined by the properties of the material (insulation) and geometry of the tank.

3.5.3.3   List of other used components

For a solar thermal system different **liquid fluids** such as thermooil, water glycol mixtures (of defined concentration) and pressurized water can be used in Polysun®. Thermal fluids can be user-defined in a high level of detail. The physical parameters such as density, thermal conductivity, heat capacity, viscosity, vapor pressure can be defined or chosen from a catalogue. Fluid mixtures are calculated with the necessary mixing terms in order to ensure the correct calculation of the fluid flow and heat transport through the pipes. **Auxillary heater** can operate with oil, gas, pellets or electricity. **Pipes** are available of different material, length and insulation which allow the calculation of pressure and heat losses in the piping system. **Heat exchanger** are available in different sizes and of different UA values and can run in counter flow or direct-current flow. The mass flow in each fluid circuit can be regulated by one **pump** and depends on its capacity curve. The mass flow is either defined by pressure drop, a set value or the match flow. A **heat consumer** can either be simulated with a *heat sink* or a hot *water demand*. A heat sink calculates the mass flow rate by defined inlet and outlet temperature and power (constant or from profile). The hot water demand requires a nominal flow rate (constant or calculated from required water volume in profile) and calculates the hot water demand with a constant inlet temperature. In Polysun7.1® several hot water demands and heat sinks can be used in one system.

3.5.4 Case Studies

3.5.4.1   Integration approach

The recently released version Polysun7.1® (2014) offers some preconfigured solar process heat system which can be modified by the user. Different types of heat transfer fluids (thermo oil, water, water glycol mixtures) can be used and pressures set individually for the solar circuit and the process loop. Template 58a represents a simple model of a solar process heat system using a constant energy sink defined by inlet/outlet temperature and mass flow rate. The heat is generated with vacuum tube collectors and transferred via an external heat exchanger to a buffer store. An external gas boiler in series with the store provides the auxiliary heat. The more complex template 58b simulates a flat plate collector field providing thermal energy with integration into a distribution network with four 4000l stores and an external oil as well as pellet auxiliary heater. The template IEA Task 49 Case1 models solar thermal integration on supply level for pre-heating of make-up water at a low temperature (<100°C). The "hot water demand" (water tap) allows a discontinuously supply of make-up water at defined temperature and set nominal mass flow rate to the system. This component is also used in template IEA Task 49 Case 4a . This template represents a simulation model of solar process heat with integration at high temperature ranges into a steam network (>250°C). Due to the fact that there is currently no steam flow model available in Polysun7.1® the steam is modelled with pressurized liquid. The latent heat transfer in the evaporator is replaced with sensible heat transfer via a heat exchanger resulting in a higher mass flow rate. The auxillary heater is used if the liquid at the outlet of the heat exchanger did not reach the required temperature.

The parameter of each component as well as the load profiles in the templates can be modified. The type of the collector, auxiliary heater and other components of the systems can be replaced easily by the above mentioned available configurations. *Vela Solaris* extends the templates of Polysun® frequently.

Alternatively the user may work with one of several templates for solar domestic hot water simulations and adapt the load profile or develop an own model.

| 58a | 58b | IEA Task 49 Case1 | IEA Task 49 Case4a |
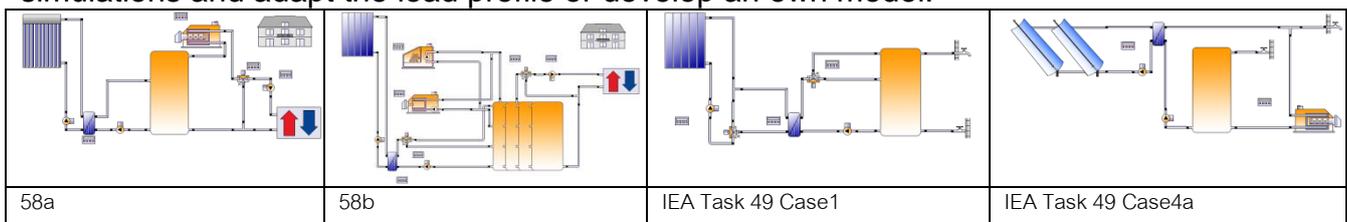
3.5.4.2   Flexibility and freedom of system design

The user is able to work with predefined templates which are given for several configurations of collector, piping system, storage and auxiliary heater. Small changes of parameters and/or replacement of components in the collector field as well as on the process side allow a quick adaptation for modelling the required process. Furthermore, several consumers can be modelled in series or parallel on the process side. In case of using measurement data for the weather profile, the software is limited to use hourly averaged values. Maximum pressure in the system is set to 50bar.

3.5.4.3   Problems and work arounds (in Case Studies)

Thanks to a high flexibility of component and system configurations and the possibility to model heat transfer at high temperatures CASE 1 – Pre-Heating of Make-up Water, CASE

2 – Bath Heating and CASE 3 – Water Heating (Return Flow Temperature Lift) and CASE 4a/b – Steam Production can be simulated within Polysun7.1®. Though, due to the absence of models for gaseous fluids, the Air collector of CASE 5 cannot be modelled with Polysun7.1®.

In case of the steam network of CASE 4a/b it has to be considered that the steam in the model is replaced by pressurized fluids. Hence, thermodynamics of the heat transfer in the heat exchanger are not equal to heat transfer mechanism (conductivity and convection) within an evaporator. The control strategy and dimensioning of both evaporators has to be realized with the aid of a different software, whereas solar gains of the collector field can be estimated.

3.5.4.4 *Limitations (in Case Studies)*

The limitations are mainly given by the component defining the load profile. The energy sink controls the flow rate by user determined inlet/ outlet temperature and power which has to be above zero in the profile. With the hot water demand the user is able to set the demand to zero, but if there is a heat demand, the volume flow is limited to the set value. Furthermore, the calculation for the heat gains in the collector field does not consider row shading or end losses.

3.5.5 Summary

Polysun® is due its graphical interface and component based structure an intuitive and little time consuming simulation software for a wide range of **solar thermal, heat pump** and **photovoltaic** systems as well as **combined systems**. It allows the calculation of yields and optimization of existing systems. A large range of preconfigured solar thermal system concepts supports the user during a quick design process of hydraulic concepts for different applications (e.g. domestic hot water systems, solar combi systems, solar district heating and solar process heat applications). Today, the software is able to simulate systems with liquid fluids of non-concentrating as well as concentrating thermal collectors. Polysun® provides some preconfigured systems for basic solar process heat applications such as pre-heating of make-up water, heating of closed process supply loops or solar thermal integration into a steam network. Though up to now the process sides are simplified by simple heat sinks and may be extended and more detailed specified by the user. Furthermore, the process temperature is limited to 250°C.

While the physical models are already very flexible and comprehensive, further plans for software extensions are in improving the graphical user interface specifically for process heat applications. This includes an improved way to import data for user-defined or measured profiles such as the heat demand or temperature profiles. While the Polysun wizard is currently optimized for the planning processes of solar rooftop and heat pump applications in the residential sector, support for the design engineer in industrial heat applications would be feasible. Vela Solaris is currently involved in a number of innovation projects and constantly extends the feature set and template database of Polysun. Improvements are shipped as incremental software updates for all active Polysun users.

3.6   Greenius (DLR/J. Dersch and S. Dieckmann)

3.6.1   Introduction

Greenius is a powerful simulation environment for the performance estimation of renewable energy projects such as solar thermal trough and linear Fresnel systems for electricity, process heat or solar cooling as well as solar towers, photovoltaic systems, wind parks or Dish/Stirling systems. This program offers a unique combination of detailed technical and economical calculations as they are needed for planning and installation of renewable power projects. Greenius has a simple and comfortable user interface and provides reliable models with low computational effort leading to simulation run times of only several seconds for a whole year with hourly resolution.

For more than ten years, Greenius was originally developed at the German Aerospace Centre (DLR) for internal use. Thanks to funding within the FreeGreenius project it is now available free of charge on freegreenius.dlr.de.

3.6.2   Mathematical background and Programming

Greenius is programmed in Delphi/Object Pascal and includes a detailed technical simulation of a typical operation year for all mentioned technologies and based on this, an economical part with cash flow overview, financing and investment key figures.

Standard temporal resolution is 1h, but finer resolutions down to 10min are possible. Greenius is able to follow a given demand profile while using a user defined operating strategy for the interaction of solar field, fossil boiler and storage.

Due to the modular data structure, all components (e.g. solar collector) of a project are saved individually an can be reused in other projects.

3.6.3   Modelling of solar thermal system

Greenius offers two different models for line focusing solar technologies. The mean temperature model is used for single-phase heat transfer fluids (HTFs). It does not account for non-linear effects over the loop length because the collector efficiency is based on the arithmetic mean temperature between inlet and outlet. The collector efficiency is determined by using the following equations.

$$\eta_{collector} = K \cdot \eta_0 - \left(K \cdot b_0 \cdot \Delta T + \frac{b_1 \cdot \Delta T + b_2 \cdot \Delta T^2 + b_3 \cdot \Delta T^3 + b_4 \cdot \Delta T^4}{DNI} \right)$$

with

$$K = IAM \cdot \cos \theta$$

$$IAM = 1 - \frac{a_1 \cdot \theta + a_2 \theta^2 + a_3 \theta^3}{\cos \theta} \qquad \text{for parabolic trough collectors}$$

The temperature difference in this equation is defined as the difference between ambient temperature and arithmetic mean temperature between collector inlet and outlet:

$$\Delta T = \frac{T_{in} + T_{out}}{2} - T_{amb}$$

For Fresnel collectors, the IAMs in transversal and longitudinal direction are interpolated

based on given tabulated values.

Another space-resolved model divides a representative loop into 12 nodes for which the individual heat balance is set up:

$$Q_i^k = \underbrace{\dot{m}_F^k \left(h_i^k - h_{i-1}^k \right) \Delta t}_{\text{convective transport}} + \underbrace{m_{F,i}^k \left(h_i^k - h_i^{k-1} \right)}_{\text{heat up fluid mass}} + \underbrace{m_W \, c_{p,W} \left(T_i^k - T_i^{k-1} \right)}_{\text{heat up wall}}$$

Q_i^k is the net absorbed solar energy of the node i at time step k. The heat balances for all nodes form a system of nonlinear equations which is solved using the solver KINSOL from the Sundials package published by the Lawrence Livermore National Laboratory. The model allows the determination of the temperature profile over the loop and leads to more accurate heat loss estimations.

The modeling of the storage depends on the chosen type. 2-Tank storages are modeled with constant heat losses. For this approach the thermal losses over 24h must be quantified as a percentage of the net storage capacity. For single tank storages the thermal losses depend on the content. The storage is characterized by a time constant which is equal to the time that leads to a reduction of the storage content from 100% to $1/e=36.8\%$ due to heat losses.

3.6.4 Case Studies

Greenius is capable of simulating many different renewable technologies from solar thermal process heat, electricity and cooling over PV to wind turbine parks. The different technologies have common components like e.g. parabolic trough collectors or storages. However the different components cannot be freely combined by the user. Instead the overall system configuration must be chosen at the beginning of the simulation project. However it is possible to take the storage out of the simulation be setting its capacity to zero.

The flexibility for the user and the level of technical details of the model is reduced which usually leads to minor simplifications of the model compared to the real system. On the other hand this reduced flexibility allows model-specific calculation routines and therewith very short simulation run times.

The process heat system implemented in Greenius is limited to the main components of such a solar steam generator: solar field, thermal storage and fossil boiler. The balance of plant (BOP) and all other necessary components are not simulated explicitly. Additional heat losses for example should be accounted to the heat losses of the solar field.

Greenius is consequently not suitable for the detailed optimization and comparison of different system configurations. Its main focus is the provision of a first guess for the performance of the system. Especially Greenius is not suitable for questions regarding integration points or pinch analyses.

3.6.5 Summary

Greenius offers fast and easy calculation of solar thermal process heat systems. The used models are focused on the main components solar field, storage and fossil boiler in order to preserve simplicity and fast computation.

The software is perfect for preliminary performance estimations within a feasibility study. It is not meant to be used for detailed engineering questions.

3.7 *EXCEL-SOPRO (ISE/W. Platzer)*

3.7.1 Introduction

EXCEL-SOPRO is a steady-state hourly calculation program which incorporates model equations for collectors, storage types and allows to calculate step by step, hour after hour, to which extent a heat demand from an industrial consumer specified by hourly heat demand, required temperature level and return temperature, can be covered by a solar thermal system.

The program calculates the solar irradiation an a collector aperture (direct and diffuse), uses steady state standard collector equations to calculate either the temperature output (for a defined massflow) or achievable mass flow) for specified outlet temperature. The heat can then be added to the energy of a storage system or directly fed to the process. Heat losses of storage and collectors are taken into account depending on the environmental temperatures. All heat required not available from the solar thermal system is assumed to be provided by an auxiliary heating.

The program is based on the EXCEL software using Visual Basic subroutines for the calculation. When changing a single input parameter predefined output summary tables and graphical presentations of results change immediately. The program thus is very flexible and transparent, as it provides also a large number of intermediate results (e.g. the temperature level of the storage, or the mass flow of the collector etc.).

Such a program could be also the basis for a future standardization as it is independent of a special software, but can be used globally.

3.7.2 Mathematical background and Programming

The mathematical background of the software is the EXCEL spreadsheet program. The values of individual cells are calculated using formulae and the results of a last time step.

3.7.3 Modelling of solar thermal system

3.7.3.1 *Collector model(s)*

The collector model used in the EXCEL-SOPRO simulations is the steady-state collector equation. The model iss used with the collector parameters given in the case description with optical efficiency η_0, with thermal loss parameters a_1 and a_2 as well as a one or twodimensional incidence angle modifiers, the basic equation being:

$$\dot{q}_{out} = \eta_0 \cdot (K_b \cdot I_b + K_d \cdot I_d) - a_1 \cdot (\vartheta_{mf} - \vartheta_{amb}) - a_2 \cdot (\vartheta_{mf} - \vartheta_{amb})^2$$

In this case due to the specifics of EXCEL a parametric representation of the incidence angle modifier curve was used (quadrativ fit in cos Θ, see Figure 4) as this allows faster calculation than interpolating between value tables. The determination of the actual heat gain and collector output is an iterative process in this model, when a fixed mass flow is chosen. In a first step, the actual collector heat gain with the inclusion of the temperature dependent thermal losses of the collector are calculated, and in a second step, the outlet temperature of the collector ϑ_{out} of this time step is calculated from the collector gain q_{gain}. In a second mode, inlet and outlet temperature are given, and only the mass flow is determined from that. No iteration is needed here.
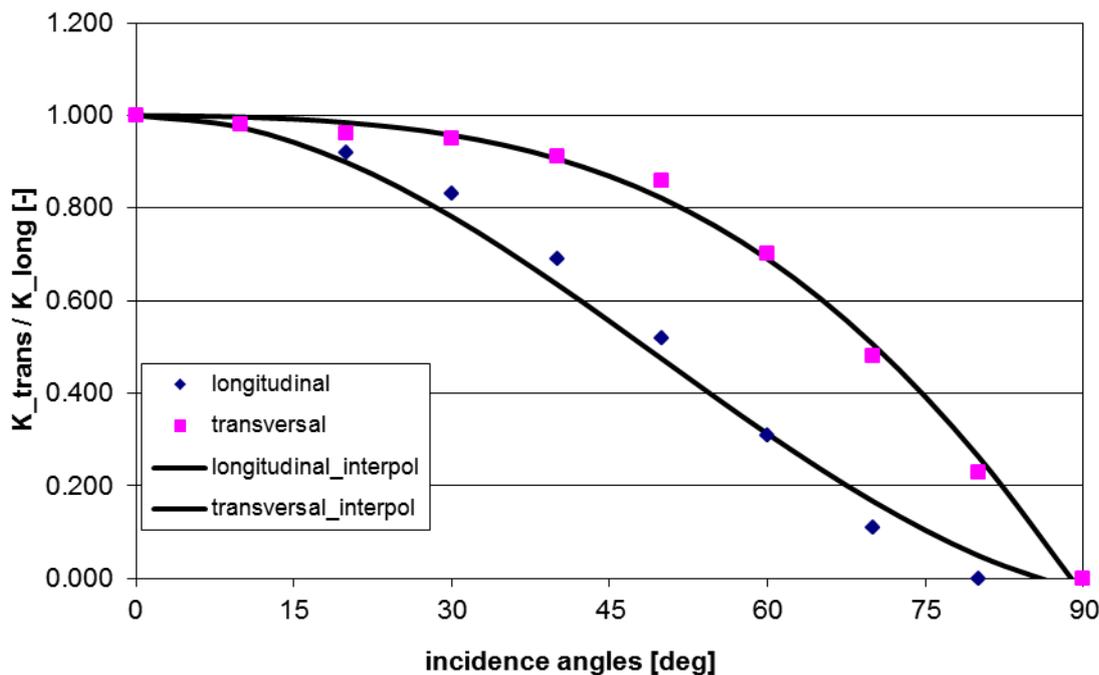
Figure 4: Example of fit function for IAM curves (Fresnel collector) with actual data

3.7.3.2   Storage Model(s)

For the storage 3 models are available. A simple mixed storage, a stratified storage with 2 sections hot and cold part, and a two-tank storage with hot and cold tank. In the case of the stratified storage the heat is preferably provided to the high temperature section and added there (thus increasing the temperature of this volume section) when collector outlet temperature is above that temperature, or to the lower cold part when it is between high and low temperature of the two section. In case the temperature is below the cold part of the storage, no charging occurs.

Temperature losses are proportional to the difference of storage temperature of the section considered and environmental temperature (which may be a fixed room temperature or the outdoor temperature). Heat exchanger with a temperature drop (say 10 K) can be taken into account. Then a higher collector temperature is needed for charging, however also the return temperature to the collector is higher.

3.7.3.3   List of other used components

The radiation processor is based on the isotropic sky model. Radiation on a tilted collector aperture can be calculated using diffuse part from sky and ground as well as the direct radiation. For the evaporation in a direct steam collector an equation was used.

For the demand profile numerical values were given for different hours within the year, depending on weekday and week in the year

Control logic is a simple logical function depending on temperatures or other physical variables of the previous state. No iteration of controller states is programmed. However in the charging/decharging there is a check that within one hour maximum and minimum temperatures are not surpassed.

3.7.3.4   Integration approach

In all the studies the hourly demand profile required a certain temperature and had a

fixed return temperature. The required mass flow at each hour thus could be calculated using a constant heat capacity of the fluid and the heat needed. This mass flow was prescribed. The heat supplied by the solar system at a given time was calculated by the mass flow and the difference between supply from the heat exchanger and the return flow of the process. The remaining heat was assumed to be supplied by the conventional source.

3.7.3.5   *Flexibility and freedom of system design*

The EXCEL-SOPRO tool is not very flexible in the overall design of systems as the formulae provide in principle a fixed system model. Some few changes can be made by flags (e.g. Storage include YES/NO). But an exchange of a component is easy as only an additional data set with new parameter values has to be created in a data base (.i.e. different collectors can be very easily compared to each other). All design values like collector area, storage volume or operation temperatures and heat profiles are easily changed. Thus it is a quick and reasonably precise tool for design purposes. New system approaches can be implemented only by modifying the formulae and require extra care.

3.7.3.6   *Problems and work arounds (in Case Studies*

The EXCEL tool does of course not provide a possibility to actually model evaporation as a two-phase process. Direct steam collectors cannot be modelled in a precise way. Up to now only an approximate modelling of evaporation was done by choosing inlet and outlet temperatures close to evaporation with an effective heat capacity including latent heat.

3.7.3.7   *Limitations (in Case Studies)*

The simulation of air collectors is possible in principle by changing the physical properties of the collector fluid, however then also the changing heat transfer due to different mass flows influencing collector efficiency should be taken into account..

3.7.4 Summary

EXCEL-SOPRO is a simple design tool for most configurations and relatively easy to use for parameter variations. It is transparent and allows access to intermediate results. The comparison with the other tools in the comparison study was surprisingly good (see e.g. Figure 5, [2-5]). The results were always within the range of all other tools. This served as a kind of validation of the new tool. On the other hand, several features have to be improved. Up to now there is no complete documentation. It is easy to accidentally delete a formula by filling in values (so sheets and cells havge to be protected). The language is in German, and still some more component data should be added to the data base. .
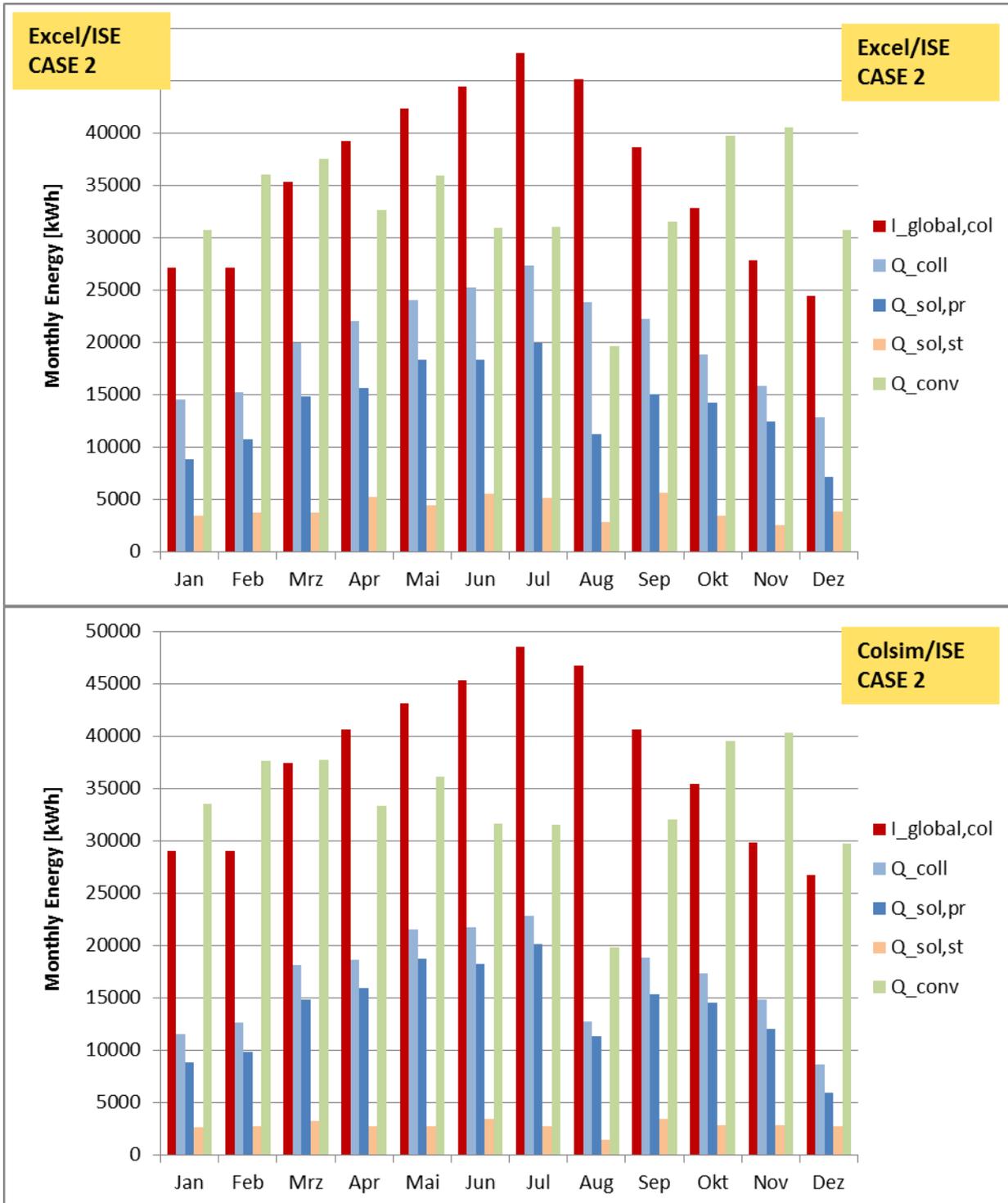
Figure 5　Monthly comparison of heat flows for Reference Case 2 -
Upper part: EXCEL-SOPRO tool; lower part: Dynamical COLSIM simulation [3]

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4   Literature References

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5   Appendix: Tabular Overview

Overview of existing **simulation tools** for solar thermal process heat simulation 1) solar thermal system simulation 2) **integration** of **process heat** loads of industrial processes.						
Tool Name	Status	Availability	developing Institution	Homepage	Publications/Manuals	Used by
TRNSYS15	research tool	commercial	Univ. Wisconsin, Madison, USA	http://sel.me.wisc.edu/trnsys/		Fraunhofer ISE; AEE INTEC; TERI
TRNSYS17	research tool	commercial	Univ. Wisconsin, Solar Energy Lab, Madison, USA	http://sel.me.wisc.edu/trnsys/		Fraunhofer ISE; AEE INTEC; IWT-TU Graz; AIT; Kassel University
GREENIUS	simple design tool	free downloadable	DLR, German Aerospace Center	http://desire.htw-berlin.de/greenius.php	http://desire.htw-berlin.de/greenius.php	DLR
TSOL	simple design tool	commercial	Dr. Valentin Energie Software GmbH	www.valentin.de	http://www.valentin.de/downloads/handbuecher	AEE INTEC
POLYSUN	professional design tool	commercial	Vela Solaris	http://www.velasolaris.ch	http://www.velasolaris.ch/vs2/index.php?article_id=105&clang=1	AEE INTEC
COLSIM	research tool	open source for redueced version	Fraunhofer ISE	http://www.colsim.org/	http://www.colsim.org/	Fraunhofer ISE
Prosol simulation tool	simple design tool/feasibility study tool	so far only in house	Politecnico Milano			Politecnico di Milano
SOLTERM	simple design tool	commercial	LNEG, IP (Portugal)	http://www.lneg.pt/iedt/projectos/370/resumo	http://dl.dropbox.com/u/3977268/SolTerm/Manual_SolTerm_5.1.3.pdf	UniEvora
T*SOL Pro		commercial	Dr. Valentin Energie Software GmbH	www.valentin.de	http://www.valentin.de/downloads/handbuecher	Commercial, Valentin
SOPRO Excel	simple design tool	only in-house	Fraunhofer ISE	www.ise.fraunhofer.de	not yet	Fraunhofer ISE

Tool Name	Collector types	Collector modelling	Storage types	Heat transfer fluids	controls
TRNSYS15	stationary and tracking	several models available	water storage	fluids with fixed capacity and density	On-Off-controller
TRNSYS17	stationary and tracking	several models available	water storage	fluids with fixed capacity and density	several controllers (differential; iterative feedback; microprocessor; PID)
GREENIUS	stationary and tracking	parametrized	water storage	single + two-phase	On-Off-controller
TSOL	stationary	several models available	water storage	fluids with fixed capacity and density	On-Off-controller
POLYSUN	stationary and tracking	parametrized	water storage	fluids with fixed capacity and density	On-Off-controller
COLSIM	stationary and tracking	dynamic models available	latent and pcm	single + two-phase	several controllers
Prosol simulation tool	based on DNI meteo file	EN 12975 (eta0, k1, k2 and IAM parameters to be input by user)	water storage	specific heat capacity and density to be input by user	On-Off-controller
SOLTERM	stationary and tracking	EN 12975 predefined and user-defined	water storage geometry and construction modelling max 5000l	fluids with fixed capacity and density	
T*SOL Pro					
SOPRO Excel	stationary and tracking	EN 12975 predefined and user-defined	fluid storage (mixed, stratified and 2-Tank)	fluids with fixed capacity and density	On-Off-controller

Tool Name	capacity effects	diffuse sky models	hydraulic solver	pinch analysis	integration of process heat	free comment
TRNSYS15	no	several models	no	no	fixed load profile	
TRNSYS17	for certain types (e.g. Type 832 collector)	several models	no	no	fixed load profile	
GREENIUS	yes	several models	no	no	fixed load profile	
TSOL	yes		no	no	fixed load profile	
POLYSUN	yes		no	no	fixed load profile	
COLSIM	yes	several models	yes	no	fixed load profile	
Prosol simulation tool	Yes:storage, piping. No: collectors		no	no	load profile to be calculated by user (3 reference weeks possible, hourly load required)	
SOLTERM					fixed load profile load hierarchy in multiple loads hourly profiles / weekday+weekend	User-defined HX possible for all pre-defined or user-defined storage systems; auxiliary system included; GHG emissions; special: swimming pool simulations TRY Portugal + user meteo data; site shading analysis
T*SOL Pro						
SOPRO Excel	no	isotropic sky	no	no	fixed load profile	still in development

Tool Name	calculation (dynamic/quasi-dynamic/stationary)	time-step	programming language	graphical user interface (GUI)
TRNSYS15	quasi-dynamic	1h	FORTRAN	IISiBAT
TRNSYS17	quasi-dynamic	1/3 min to 1h	FORTRAN	Simulation Studio (Version 16/17)
GREENIUS	steady state with consideration of the thermal inertia of HTF and piping	1h	Delphi (Object Pascal)	The GUI is an intrinsic part of the software
TSOL	quasi-dynamic	6 min (monthly) to 1 hour (annual) simulation	(ursprünglich) FORTRAN	
POLYSUN	quasi-dynamic	automatically no change possible		
COLSIM	dynamic	1 s to 1 h	ANSI-C	XFIG
Prosol simulation tool	quasi-dynamic	1 h	TRANSED application of TRNSYS (FORTRAN)	Fixed plant schemes (1 for low T, 1 for High T); input data via excel file, parameters to be input directly into TRANSED (GUI)
SOLTERM	quasi-dynamic	600 s	Visual Basic	Visual Basic
T*SOL Pro	dynamic	6 minutes in general. 1 minute, if needed!	Pascal (Borland Turbo Delphi)	standard Windows UI
SOPRO Excel	steady state	1h	Visual Basic	Excel

Tool Name	problems and limitations for current version	free comments
TRNSYS15	time step too large for fast changes (e.g. operational); steam available for Vers. 16 in STEG library, but not in distributed version	
TRNSYS17	time step too large for fast changes (e.g. operational); steam available	TESS Library "High temperature solar" avalaible for steam; linear parabolic concentrator in TESS Solar library
GREENIUS	The current time step restriction is due to the 3rd-party software for result display and analysis. This 3rd party software shall be replaced soon.	Currently Greenius is not freely available but a full free version shall be published by end 2012. This version shall be able to use smaller time steps down to e.g. 10 minutes
TSOL	very limited variability regarding simulation of process heat applications (only one heat sink possible which is defined by the hourly energy demand and one fixed supply and return temperature)…	
POLYSUN	only a few hydraulic schemes for process heat available, self-defined schemes can cause problems with controller ….	
COLSIM	not all components yet validated; no heat-exchanger-network-optimization	
Prosol simulation tool	currently not user friendly, optimization needed.	
SOLTERM	Two-phase flows not allowed; fixed HTF (variable mix water+glicol, only liquid phase)	thermal, economical and GHG emissions output
T*SOL Pro	-	3 predefined systems for solar thermal process heat either with or without backup heater. Parameters for process heat demand: pre-defined and user-defined hourly based annual profiles, operation periods, temperature levels
SOPRO Excel	only a few hydraulic schemes for process heat available, no fool-proof user interface	