

**A TRNSYS Model Library  
for Solar Thermal Electric Components  
(STEC)**

**Reference Manual  
Release 3.0  
November 2006**

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## DISCLAIMER

The STEC model library is *freeware*. With installing this software you accept that the use is at your own risk and no warranty is provided for the quality of the software or the results obtained while using this software.



## **Preface of the current Edition**

### **Release 3.0**

The third full new release of the TRNSYS model library STEC (solar thermal electric components) is available – with some delay! The versions of the TRNSYS simulation environment seem to change faster these days than users can follow. But a couple of big improvements justify the upgrade (especially the feature of drop-in-dlls is a great advantage for user-written model libraries). Therefore, the models of the STEC library were updated to TRNSYS16 standard with the great help of TRNSYS engineer Diego A. Arias.

While the standard TRNSYS users seem to intensify their focus on building simulation and energy supply a growing group of engineers world wide are interested in solar thermal power systems. When the first release started more than eight (!) years ago as a SolarPACES activity the intention was to provide a rather simple simulation tool that allowed researchers to become familiar with solar thermal power system behaviour. Today, the STEC library is distributed to more than 30 persons or institutions world wide. The models are used in research and development as well as in commercial projects. One impulse of interest was the free distribution of the STEC library also to non-SolarPACES members in 2003. But lately, with numerous commercial solar thermal power projects emerging -mostly in Europe and the U.S.- the interest is even increasing and moving from public research to private business institutions.



The status of the STEC model library is *freeware* with full access to the source code. This open status shall be maintained. The models are developed, written and tested by STEC-users. The distribution of the STEC library is a non-budget activity, currently conducted by DLR. Therefore, the library's content and its quality is reliant on the contribution and collaboration of the single user. All recipients are again strongly invited to improve the STEC library by adding own components or projects, by validating models with other codes or measurements or by giving comments and suggestions to the developers.

November 2006

Peter Schwarzbözl

## Prefaces to former editions

### Release 1.0

This is the first version of the Reference Manual of the TRNSYS Model Library of Solar Thermal Electric Components (STEC). This document gives an overview on the intention of this library, its theoretical background, and on the structure of the library. It also presents some sample applications to demonstrate how the components can be set-up in an assembly. The appendix gives technical information on the hardware and software system requirements, how to install the library, as well as a complete documentation on all models distributed with the STEC library. This document does not intend to replace the software description of TRNSYS and its user interface IISibat. Applicants of the STEC library should have a basic understanding of TRNSYS and on the IISibat Interface.

TRNSYS and the STEC Library are tools which help technical experts to analyse the performance of a solar thermal power system in detail. On the basis of models which are set-up by these expert users, the TRNSYS tool TRNSED can be used to convert this model into a black box software program, that is easy to operate by non-technical experts for performing parameter variations, system studies, or comparisons with actual plant output. No software or license need to be purchased to use a TRNSED model. However, in order to develop or operate models in TRNSYS using the STEC model library, the user must have a valid software license of the TRNSYS code and the IISibat user interface. The STEC library itself is distributed for free and without any warranty Please ask for a copy (Robert.Pitz-Paal@dlr.de), which will be send to you by email. Comments and bug reports are highly appreciated. Also modifications of the code and the development of the new STEC models (e.g. Dish concentrator, receiver, Stirling engine, improved central receiver models...) are of high interest and a copy of the code (send by email) would be highly appreciated and will be considered to be included into the next STEC release.

October 1998

Robert Pitz-Paal

Scott Jones

## **Release 2.0**

The models of the STEC library are permanently used and improved since the first release in 1998. The STEC library was upgraded for compatibility with the new TRNSYS 15 and lisibat3 by former TRNSYS engineer Nathan Blair from University of Wisconsin in summer 2000. Few changes have been made to the steam generation models of the Rankine sublibrary. In the STE sublibrary a new trough model was added with improved modelling of startup and shutdown of parabolic trough fields (Type196). The former Type96 is now called 'oldtrough' and has the new type number 197. Some other new models were added, mostly for improved modelling of solar cycles. The model library for gas turbine cycles, created by colleagues from the IVTAN institute in Moscow (Russia), was adapted to the standard TRNSYS modelling approach and now belongs to the STEC library as the Brayton sublibrary.

To ensure STEC library users are committed to contribute their new developments to the library in exchange for using it for free, a formal SolarPACES agreement has been created (see next page). It has to be signed before receiving the new release 2.0 .

This document is an update of the SolarPACES Technical Report No.III – 4/98 (Reference Manual for the STEC library release 1.0 from October 1998). It was revised and adapted according to the new TRNSYS 15/ lisibat3 features. The explanation of a new example project was added (see Example 3 in Chapter 5). The former Appendix A3 containing the model headers as documentation is no longer maintained and therefore not included in this document. Users are advised to refer to the lisibat proforma for model documentation.

March 2001

Robert Pitz-Paal

Peter Schwarzbözl

## Release 2.2

One year and a half have past since the last release of the TRNSYS STEC model library and quite a lot of new developments have been made since then. Therefore, this new release contains more than 20 new types and a couple of new property routines.

The Rankine sublibrary has been restructured and now contains only one – the latest – version for each component. Two new types have been added by our US-colleagues for improved turbine control in start-up and shut-down procedures. The biggest improvements have been made to the Brayton sublibrary, which has now two new sections – ‘CIEMAT’ and ‘DLR’ – containing each a complete set of gas turbine cycle components. They have different advantages and disadvantages and users should decide themselves which modelling approach suits best for their purposes. The Solar Thermal sublibrary has a new trough subsection called ‘CIEMAT’, containing a couple of new types with a more sophisticated modelling approach for parabolic trough collectors. Further on, two new tower receiver models have been added to this sublibrary. All the other models have been revised and several bugs could be fixed. Model documentation was revised as well and is maintained on two levels: Basic descriptions of each type can be found in the corresponding lisibat proforma. Additionally, if available, more detailed documentation about important components or complicated models was added to this Reference Guide. For further questions the user should try to contact the author / editor of the type directly.

The DLR, as the official ‘keeper’ of the STEC model library, is collecting new developments from the users, adding documentation and example projects and putting together new releases every one or two years to distribute for free among registered SolarPACES members. Therefore, the DLR and the other authors of the STEC models can not be made responsible for the functionality of this software and the results obtained while using it. Furthermore, as the DLR has no extra budget for the STEC activity, the support of users has to be limited to a small level.

Last but not least the authors wish to express their gratefulness to the users, who contributed own models to the library or gave important remarks to improve the existing ones, and appeal to the others to share their developments with all the colleagues of this user group.

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## INTRODUCTION

Performance calculations are necessary to assess the feasibility of proposed solar thermal power plants and to monitor their performance once operational. The SOLERGY code [1], created by Sandia National Labs in the mid-eighties, had become a quasi-standard for estimating the annual performance of solar thermal plants. However, the capabilities and the ease of use of SOLERGY are not up to date with today's standards of computing power and user-friendliness. SOLERGY is limited to energy flow calculations for a hard-wired plant configuration. This has required changes to the FORTRAN source code to adapt to different plant configurations- for instance, LUZERGY was created to handle plants without storage. This complication is now especially restrictive because of the many hybrid cycle concepts combining solar radiation and fossil heat input that have been recently proposed to facilitate the market penetration of solar thermal power plants.

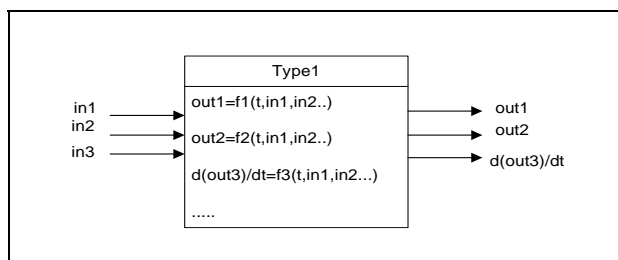
TRNSYS and its user interface IISibat were selected for this objective because they permit the user to use predefined components or create their own FORTRAN component models with defined input and output interfaces that can be easily connected to create arbitrary systems. Models of varying complexity such as simple energy balance models (like SOLERGY), more complex steady-state thermodynamic models, or even simple transient thermodynamic models can be implemented. Moreover, the availability of TRNSYS source code and its reasonable price may increase the acceptance of this software in the solar thermal power community and may help to increase the library's use by others.

~~1 AND SECOND, A COMPARISON BETWEEN ACTUAL SOLAR TWO OPERATING DATA AND TRNSYS PREDICTIONS.~~

~~2~~

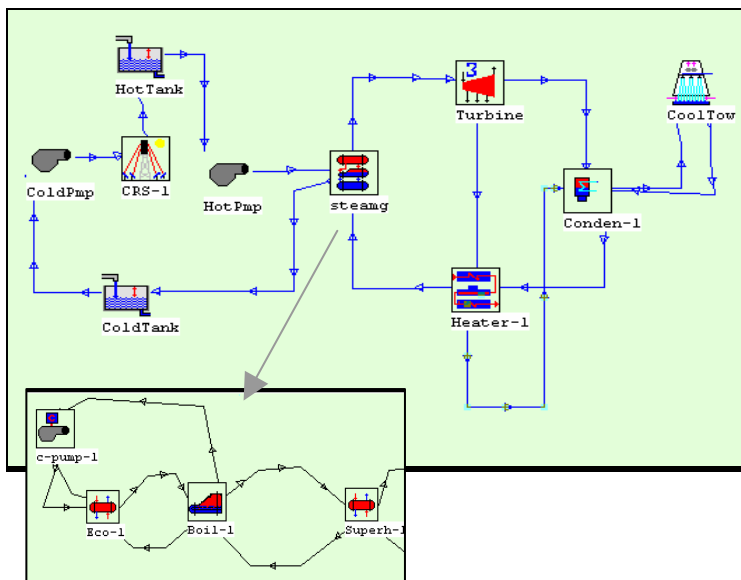
## 1 THE TRNSYS COMPUTER CODE AND THE IISIBAT USER INTERFACE

TRNSYS has been under development at the University of Madison, WI, for more than 20 years. Its major field of application is the evaluation of solar systems for heating and cooling purposes and domestic hot water applications. However, the flexibility of the code results in the fact that a world-wide user group has created component models in many other application fields. The version 14.2 of TRNSYS with the IISiBat 2 (graphical) interface was used for the first release of the STEC library. It was upgraded for TRNSYS version 15 and Iisibat 3 and now to TRNSYS16 and the Simulation Studio.



**Figure 1: Principle of a TRNSYS component subroutine**

The principle philosophy behind TRNSYS is the implementation of algebraic, and first-order ordinary differential equations describing physical components into software subroutines (called types) with a standardised interface. This interface consists of so called "input" and "output" quantities. Outputs can be either physical quantities or first order derivatives (with time) of physical quantities. The functional relations between inputs and outputs are defined in each subroutine (see Figure 1). To create a system model, the user simply connects the outputs of components with the inputs of other components. The user does not have to worry about how to solve the complex set of equations resulting from the system layout because the TRNSYS kernel performs this function by successive substitution or Powel's Method.



**Figure 2 : The User Interface supports graphical connections, set-up of initial values and creation of macros**

A variety of utility components help to handle input from data files, generate forcing functions, print, plot, integrate or interpolate data. These utilities are linked to the physical components in exactly the same way as described above.

The user interface named 'Simulation Studio' has significantly improved the capabilities of TRNSYS. Its major features are displayed in Figure 2 and summarised here:

- A graphical user interface using an assembly window in which the components are represented by icons and the connections among them are represented by lines with one line shown for each set of component inputs and each set of component outputs to improve readability.
- The creation of macro components. Complex systems usually consist of a huge number of components and links, resulting in a confusing graphical representation. To avoid this, there is the option to combine a group of components and their links in a macro, which is displayed as a single icon thereafter. The user can „zoom“ in to or out of a macro to display the desired level of detail.
- Assistance with unit conversion and automatic checking that input values are within bounds.
- Easy integration of new component models, supported by an icons generator, input masks generator and FORTRAN software templates, as well as documentation support. ~~'Analyst' level users are allowed create system layouts and perform calculations. 'Conceptor' level users may additionally create and modify components. Components and macro components can be stored in hierarchically structured libraries, which are owned by the users. Normally, users are limited to read-only access to the libraries created by others.~~
- Support for parametric studies with automated batch processing



**SolarPACES**



These major features of the graphical interface to TRNSYS help to set-up problems efficiently and with a low probability of making errors.



~~Additionally, it supports multi-user development in parallel and helps to create preliminary documentation.~~

## 2 THE STEC MODEL LIBRARY THEORETICAL BACKGROUND

The STEC library is based on steady-state energy conservation (1<sup>st</sup> and 2<sup>nd</sup> laws) formulated in thermodynamic quantities (temperature, pressure, enthalpy). It consists of models suitable for Rankine cycles, solar systems (central receiver, heliostat field, and parabolic trough models), storages and Brayton cycles. TRNSYS standard components also include models for a storage tank and a rockbed storage. In order to consider transient effects like start-up, an 'capacity' model has been developed that can be linked to each of the previously mentioned components and easily tuned to match empirical data. This permits thermal capacity to be considered only in those components where it has a big impact, and avoids the huge gain in computational complexity of a full transient model. The quasi-steady-state formulation of most component models also simplifies their validation through comparison to steady state results from commercial power cycle codes.

The most challenging task for the development of new library component models is the definition of the input and output quantities because this has a major impact on flexibility, number of control components required, and computational complexity. Therefore, it is not always the best choice to use physical inlet conditions of a component as TRNSYS inputs and physical outlet conditions as TRNSYS outputs. If we consider, for example, the inlet and outlet quantities for a water-steam kettle evaporator that is heated by a single phase fluid (like flue gas). The choice of water and flue gas inlet temperatures, pressures, and mass flows as inputs and the respective outlet quantities as outputs would result in the problem that both mass flow rates are not independent of each other since the outlet steam is limited to saturated conditions. One would need an additional, external controller that would set a pump speed to meet the outlet conditions. A simpler approach is to define the water flow rate as an output quantity, calling it 'demanded water flow'. This could be connected directly to a pump component, so that the flow rate through all other components connected in series with the evaporator is fixed by this set-up and no further controller is needed. This idea of a 'flow demand' as an output is used in several components. A preheater for example demands for a steam flow to the extraction of a turbine, or an attemporator demands for a feed water flow rate.

### 3 STRUCTURE OF THE LIBRARY

The appearance of the new Simulation Studio is similar to Iisibat 3. Component models are represented by so-called 'proforma' files with the file extension \*.tmf. Project files (assemblies of linked models to simulate a technical system) have the file extension \*.tpf. Both are stored in the normal Windows® file structure and can be accessed and manipulated through the Studio. The STEC Lib consists of four component libraries named 'Rankine' for the Rankine cycle components, 'STE' for solar thermal components, 'Brayton' for the gas turbine cycle components and 'Storage' for the components which describe high temperature thermal storage systems. Some example projects can be found in the folder 'STEC\_examples'.

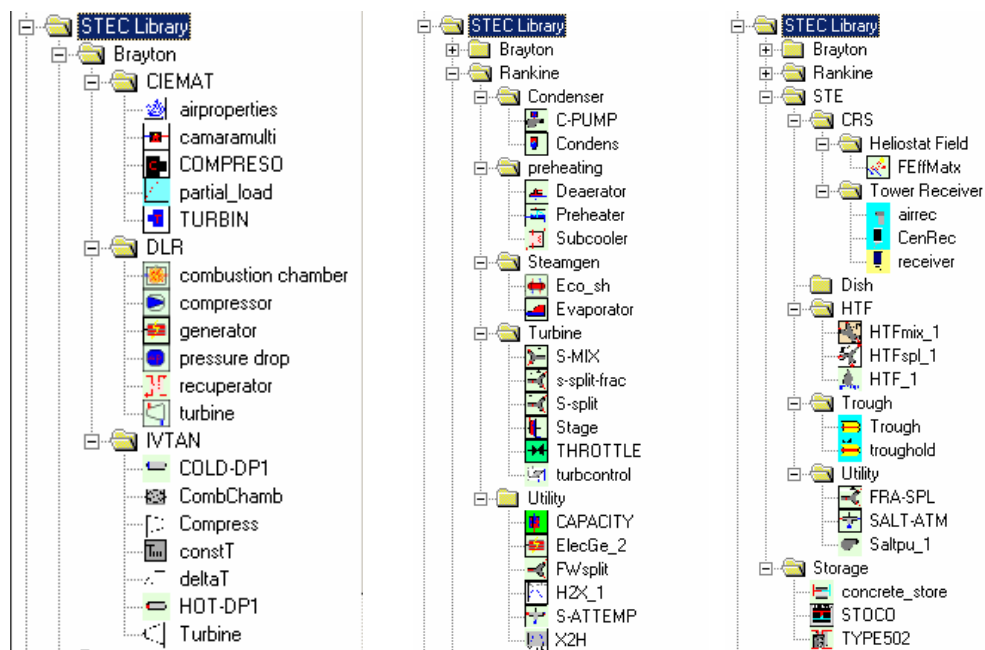


Figure 3: a) Brayton Library b) Rankine Library c) STE- and Storage-Library

### 3.1 THERMODYNAMIC PROPERTY ROUTINES OF THE STEC LIBRARY

#### Boil

OBJECTIVE: For given pressure  $p$  in bar the routine returns saturation condition  $ts[^\circ\text{C}]$   $hs,r[\text{kJ/kg}]$ . It uses real function lin4 for linear interpolation of data.

Matrix data from VDI Waermeatlas, VDI Duesseldorf 84

For given temperature  $T$  in  $^\circ\text{C}$  the routine returns saturation condition  $ps[\text{bar}]$   $hs,r[\text{kJ/kg}]$ . It uses real function lin4 for linear interpolation of data

Matrix data from VDI Waermeatlas, VDI Duesseldorf 84

#### Steam 3

OBJECTIVE: Given any two steam properties, this routine evaluates the remaining properties associated with the state.

NOTICE: The range of validity for this model does not include the supercooled liquid range.

A call to this routine has the following form:

```
CALL STEAM(UNITS,T,P,H,S,Q,V,U,ITYPE)
```

where UNITS is a character variable (declared as CHARACTER\*2) and/or set equal to "SI" or "EN".  $T$ ,  $P$ ,  $H$ ,  $S$ ,  $Q$ ,  $V$ , and  $U$  are the steam temperature (deg. C, deg. F), pressure (MPa, psia), enthalpy (kJ/kg, Btu/lbm), entropy (kJ/kg-deg.C, Btu/lbm-deg.F), quality, specific volume ( $\text{m}^3/\text{kg}$ ,  $\text{ft}^3/\text{lbm}$ ), and internal energy (kJ/kg, Btu/lbm), and ITYPE refers to which of the 7 arguments are specified as known properties. For example, in the following call to STEAM, properties for steam would be evaluated at a temperature of 1000 degrees Fahrenheit and pressure of 900 psi absolute.

```
CALL STEAM('EN',1000.,900.,H,S,Q,V,U,12)
```

A quality larger than 1 is a flag that the steam is a superheated vapour. In order to specify a saturated vapour or liquid condition, use a quality of 1. or 0. along with any additional property.

## Gas

OBJECTIVE: This routine evaluates the properties of gas mixtures which consist of the components : Ar, Ne, N<sub>2</sub>, O<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, SO<sub>2</sub>, air and airnitrogen. The calculation is based on equations, which determine the gas properties exactly in the temperature range of 200 K – 1800 K.

For input the routine requires:

- combinations (*prop 1- 4*) of temperature (°C), pressure (bar), enthalpy (kJ/kg) and entropy (kJ/kgK)
- the mixture of the gas as mass ratio of the components (*mix 1- 10*)
- the calculation mode (*itype 1, 2, 3 or 4*)

A call to this routine has the following form:

```
CALL Gas(prop, mix, itype, ierr)
```

here *itype* = 1 means given temperature and pressure → evaluate enthalpy and entropy  
*itype* = 2 means given pressure and entropy → evaluate temperature and enthalpy  
*itype* = 3 means given pressure and enthalpy → evaluate temperature and entropy  
*itype* = 4 means given temperature and entropy → evaluate pressure and enthalpy

For example, a call to Gas with

```
prop 1 = 1600  
prop 2 = 12  
mix 1-8 = 0  
mix 9 = 1  
mix 10 = 0  
itype = 1
```

would supply the enthalpy and the entropy for air at the temperature of 1600 °C and pressure of 12 bar absolute.



## 3.2 MODELS OF THE BRAYTON SUBLIBRARY

### 3.2.1 CIEMAT models

#### Air properties (Type 401)

OBJECTIVE: This type has as output the thermodynamic properties of air, it uses a polynomial fit of the variable-temperature data and a correction with the pressure in density, entropy and enthalpic exergy

TRNSYS COMPONENT CONFIGURATION:

PARAMETERS: None

INPUTS:

Temperature (C)  
Pressure (bar)

OUTPUTS

Density Kg/m<sup>3</sup>  
Specific Heat kJ/kgK  
Viscosity Poises  
Thermal conductivity W/mK  
Gamma (Cp/Cv) sans dimensions  
Enthalpy kJ/kg  
Entropy kJ/kgK  
Internal Energy kJ/kg  
Enthalpic exergy kJ/kg

#### Compressor (Type 403)

OBJECTIVE: This type is an adiabatic compression of air and determines the compression work and the outlet temperature. As a characteristic parameters of each compressor, the type use two parameters: the adiabatic and mechanical efficiencies.

$$W = \frac{P_{in} V_a \gamma \left[ \left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{(\gamma - 1) \eta_{ac} \eta_{mc}}$$

$$T_{out} = T_{in} \left[ \frac{\left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{dc}} + 1 \right]$$

W = Absorbed Power  
 P<sub>in</sub> = Inlet Pressure  
 P<sub>out</sub> = Outlet Pressure  
 T<sub>in</sub> = Inlet Temperature  
 T<sub>out</sub> = Outlet Temperature  
 V<sub>a</sub> = Flow rate (at inlet condition)  
 γ = C<sub>p</sub>/C<sub>v</sub>  
 η<sub>ac</sub> = Adiabatic efficiency  
 η<sub>mc</sub> = mechanical efficiency

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

Mode (operation mode,  
     MODE=1, compression rate as a input  
     MODE=2 compression work as a input  
 R\_adiabatic Adiabatic efficiency  
 R\_mechanical Mechanical efficiency

##### INPUTS:

Inlet\_pressure (bar)  
 Inlet temperature (C)  
 Compression rate (P\_outlet/P\_inlet)  
 Flow\_rate (kg/h)  
 Compressor work (kJ/h) (mode=2)

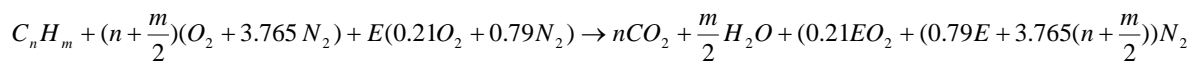
##### OUTPUTS

Specific\_work (kJ/kg)  
 Compression\_power (kW)  
 Compression\_work (kJ/h)  
 Outlet temperature (C)  
 Outlet\_pressure (bar)  
 Outlet\_flow\_rate (kg/h)  
 Gamma

#### Combustion Chamber (Type 404)

OBJECTIVE: This type is a combustion chamber of different fuels (identified by the Lower Heat value and the carbon and hydrogen atom number in the fuel chemical formula, as an example methane is 1 carbon and 4 hydrogen atoms).

Combustion reaction:



$$T_{outlet} = \frac{LHV}{Q * cp_{exhaust\ gases}} + T_{inlet}$$

The model uses as input the air mass flow rate and the outlet set point temperature and determines the fuel use and the excess air in the combustion reaction in order to reach the outlet temperature.

TRNSYS COMPONENT CONFIGURATION:

PARAMETERS:

- MODE (combustion mode)
- MODE=1, temperature set point, air mass flow as input
- MODE=2, air and fuel mass flow rate as input
- LHV Fuel Lower Heat value (kJ/kg)
- n= Carbon number in the chemical formula
- m=Hydrogen number in the chemical formula
- Eff Combustion efficiency
- Max\_fuel: Maximum fuel mass flow rate of the combustion chamber kg/h

INPUTS:

- Inlet\_temperature (C)
- Inlet\_pressure(bar)
- Mass\_flow: Air mass flow rate (kg/h)
- Fuel\_mass flow (MODE=2)(kg/h)
- Compressor\_specific work (kJ/kg) (stage\_number=1)

OUTPUTS

- Outlet temperature (C)
- Fuel:use (kg/h)
- Exhaust gases mass flow rate(kg/h)
- Exhaust gases volumetric flow rate (m3/h)
- Energy use (kJ/h)
- Excess air (%)
- Exhaust mass flow rate of CO<sub>2</sub>, H<sub>2</sub>O, N<sub>2</sub>, O<sub>2</sub>)
- %Water in the exhaust gases

### Turbine (Type 405)

OBJECTIVE: This type is an adiabatic expansion of air and determines the generated work and the outlet temperature. As characteristic parameters of each stage, the type use two parameters: the adiabatic and mechanical efficiencies.

$$W = \eta_{mt} \eta_{at} \frac{P_c V_c \gamma}{\gamma - 1} \left[ 1 - \left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

$$T_{out} = \eta_{at} T_{in} \left[ \left( \frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] + T_{in}$$

W = Generated Power  
 P<sub>in</sub> = Inlet Pressure  
 P<sub>out</sub> = Outlet Pressure  
 T<sub>in</sub> = Inlet Temperature  
 T<sub>out</sub> = Outlet Temperature  
 V<sub>a</sub> = Flow rate (at inlet condition)  
 γ = C<sub>p</sub>/C<sub>v</sub>  
 η<sub>at</sub> = Adiabatic efficiency  
 η<sub>mt</sub> = mechanical efficiency

### TRNSYS COMPONENT CONFIGURATION:

#### PARAMETERS:

Stage number: Expansion stage number  
 R\_adiabatic Adiabatic efficiency  
 R\_mechanical Mechanical efficiency

#### INPUTS:

Inlet\_pressure (bar)  
 Inlet temperature (C)  
 Pressure ratio (P\_inlet/P\_outlet) (stage number>1)  
 Flow\_rate (kg/h)  
 Compressor\_specific work (kJ/kg) (stage\_number=1)

#### OUTPUTS

Specific\_work (kJ/kg)  
 Expansion\_power (kW)  
 Expansion\_work (kJ/h)  
 Outlet temperature (C)  
 Outlet\_pressure (bar)

Outlet\_flow\_rate (kg/h)  
Pressure ratio

### Partial load performance (Type 402)

OBJECTIVE: This subroutine determines the energy generated (like turbine) or absorbed (like compressor) as a function of the part load rate with two efficiency data (at maximum and intermediate load rate)

TRNSYS COMPONENT CONFIGURATION:

PARAMETERS:

Mode lineal/hyperbolic  
Mode=1 lineal fit  
Mode=2 hyperbolic fit  
Mode energy generator/absorber

INPUTS:

Input load : Load to determine the efficiency  
max\_load: maximum load of the system  
Max\_eff: Efficiency at maximum load  
Partial\_load 2: Second Load rate (second data)  
eff\_2: Efficiency at the partial\_load 2 (second data)

OUTPUTS:

%load: Load rate at the input load  
Eff\_to\_max: Effectivity respect to the maximum efficiency  
System\_eff. System efficiency  
Input\_load: ideal load  
Output\_load: Real load in function of the system efficiency

## 3.2.2 DLR models

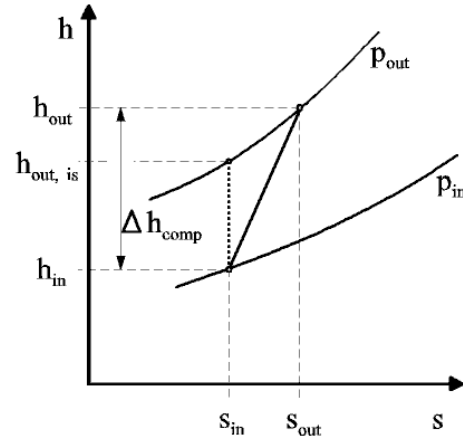
### Compressor (Type 424)

OBJECTIVE: This compressor model calculates the outlet conditions from the inlet state by using an isentropic efficiency which can be specified by the user as a function of the flow rate. In this way, the model calculates for a given compressor ratio the outlet- temperature  $t_{out, is}$  and -enthalpy  $h_{out, is}$  for an isentropic compression by calling the Gas routine (call Gas with the inputs  $p_{out}$  and  $s_{out, is} = s_{in}$ ). The real outlet conditions are then calculated by using the isentropic efficiency and a new call of the Gas routine (call Gas with the inputs  $p_2$  and  $h_2$ ).

$$\Delta h_{compressor} = \frac{h_{out, is} - h_{in}}{\eta_{isentropic}}$$

$$h_{out} = h_{in} + \Delta h_{compressor}$$

$$P_{compressor} = \frac{\dot{m}_{out} \cdot \Delta h_{compressor}}{\eta_{mech.}}$$



#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

- compression ratio
- mechanical efficiency
- ISO inlet mass flow\_design kg/hr
- partial load by mass flow reduction if mode 2
  - limited the mass flow when it is an input
- operating mode
  - mode = 1 : inlet mass flow as a function of the inlet conditions
  - mode = 2 : inlet mass flow as an input

##### INPUTS:

- inlet air temperature C
- inlet pressure BAR
- inlet mass flow if mode 2 kg/hr
- isentropic efficiency\_design
  - to be specified by the user
- cooling air mass ratio
  - evaluated by the turbine model (to cool the blades)

##### OUTPUTS:

- outlet temperature C
- outlet pressure BAR
- outlet mass flow working air kg/hr
- outlet mass flow cooling air kg/hr
- actual compressor power kJ/hr
- relative compressor power (Pve/mse) kJ/kg
- outlet enthalpy kJ/kg
- total outlet mass flow kg/hr

#### Combustion Chamber (Type 426)

OBJECTIVE: This model describes an adiabatic combustion chamber for different liquid or gaseous fuels. The user has to define the fuel by the lower heating value and the mass ratio of the fuel elements : C, H<sub>2</sub>, S, O<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>O, ash and airnitrogen given in the organic analysis. The model allows two different operating modes- in the first case for a given outlet temperature the required fuel mass flow is calculated, in the other way the reached temperature results from the fuel flow used. Beside that a pressure loss is evaluated, based on a user specified reference value as a function of inlet conditions.

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

- operating mode
  - mode = 1 : outlet temperature as a result of given fuel flow rate
  - mode = 2 : fuel flow rate as a result of given outlet temperature
- lower calorific value kJ/kg
- C mass ratio
- H<sub>2</sub> mass ratio
- S mass ratio
- N<sub>2</sub> mass ratio
- O<sub>2</sub> mass ratio
- H<sub>2</sub>O mass ratio
- ashes mass ratio
- relative pressure drop\_design  
design or off-design (mode 3 or 4)
  - pressure loss independent/dependent from the inlet conditions
- inlet temperature\_design if mode 4 C
- inlet pressure\_design if mode 4 BAR
- inlet mass flow\_design if mode 4 kg/hr

##### INPUTS:

- inlet air temperature C
- inlet air flow rate kg/hr
- fuel flow rate if mode 1 kg/hr
- outlet temperature if mode 2 C
- inlet pressure BAR
- inlet enthalpy kJ/kg

##### OUTPUTS:

- outlet temperature C
- fuel mass flow kg/hr
- outlet mass flow combustion air kg/hr
- outlet pressure BAR
- air ratio
- CO<sub>2</sub> mass ratio
- H<sub>2</sub>O mass ratio
- SO<sub>2</sub> mass ratio
- airnitrogen mass ratio

air mass ratio  
 outlet mass flow CO2 kg/hr  
 fuel heat flow kJ/hr  
 specific minimum air quantity  
 outlet enthalpy kJ/kg

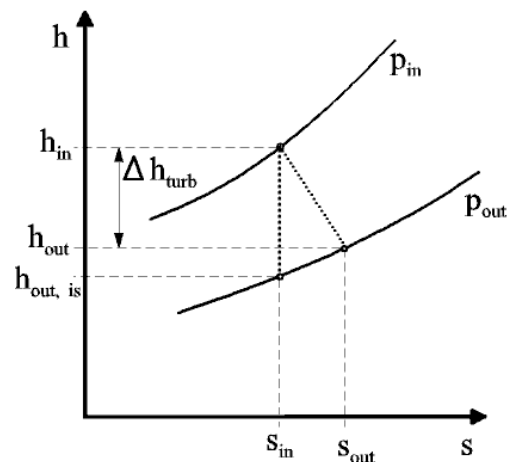
### Turbine (Type 427)

OBJECTIVE: This gas turbine model calculates the outlet conditions from the inlet state by using an isentropic efficiency which can be specified by the user. In this way, the model calculates for a given ambient pressure and therefore known turbine outlet pressure first the outlet- temperature  $t_{out, is}$  and -enthalpy  $h_{out, is}$  for an isentropic expansion by calling the Gas routine (call Gas with the mixture of the combustion air and the inputs  $p_{out}$  and  $s_{out, is} = s_{in}$ ). The real outlet conditions are then calculated by using the isentropic efficiency and a new call of the Gas routine (call Gas with the mixture of the combustion air and the inputs  $p_2$  and  $h_2$ ). For the inlet state the model considers the merge of the combustion- and cooling- air by computation new inlet conditions for the mixture.

$$\Delta h_{turbine} = \frac{h_{in} - h_{out, is}}{\eta_{isentropic}}$$

$$h_{out} = h_{in} - \Delta h_{turbine}$$

$$P_{turbine} = \dot{m}_{in} \cdot \Delta h_{turbine} \cdot \eta_{mech.}$$



TRNSYS COMPONENT CONFIGURATION:

#### PARAMETERS:

mechanical efficiency  
 maximum inlet temperature without cooling C  
 ambient pressure BAR  
 maximum inlet temperature with cooling C

#### INPUTS:

temperature combustion air C  
 temperature cooling air C  
 inlet pressure BAR



mass flow combustion air kg/hr  
 mass flow cooling air kg/hr  
 isentropic efficiency  
 CO2 mass ratio  
 H2O mass ratio  
 SO2 mass ratio  
 air mass ratio  
 airnitrogen mass ratio  
 relative pressure drop\_exhaust silencer  
 relative pressure drop\_heat exchanger\_hot side  
     → optional for a recuperative cycle  
 inlet enthalpy working air kJ/kg  
 inlet enthalpy cooling air kJ/kg

OUTPUTS:

outlet temperature C  
 outlet mass flow kg/hr  
 actual turbine power kJ/hr  
 relative turbine power (Pte/ma) kJ/kg  
 cooling air mass ratio  
 outlet enthalpy kJ/kg  
 outlet pressure BAR

### 3.3 MODELS OF THE RANKINE SUBLIBRARY

#### Eco\_SH (Type 315)

OBJECTIVE: A zero capacitance sensible heat exchanger is modelled in counter flow mode. The cold side input is assumed to be water/steam depending on the xci quality. The respective cpc specific heat of the cold side fluid is calculated from water/steam property data. The effectiveness  $\eta_{ECO}$

$$\eta_{ECO} = \frac{1 - e^{-\frac{UA}{\dot{C}_{min}} \left(1 - \frac{\dot{C}_{min}}{\dot{C}_{max}}\right)}}{1 - \frac{\dot{C}_{min}}{\dot{C}_{max}} \cdot e^{-\frac{UA}{\dot{C}_{min}} \left(1 - \frac{\dot{C}_{min}}{\dot{C}_{max}}\right)}}$$

is calculated by using the overall heat transfer coefficient UA. UA is evaluated from the power law

$$UA = UA_{ref} \cdot \left( \frac{\dot{m}_{cold}}{\dot{m}_{cold,ref}} \right)^{UA\_exp}$$

Where  $UA$  is limited between  $0.1 \cdot UA_{ref}$  and  $2 \cdot UA_{ref}$ .  $UA_{ref}$ ,  $\dot{m}_{cold,ref}$  and  $UA\_exp$  can be specified by the user. Additionally a pressure loss is scaled in the same way:

$$\Delta p = \Delta p_{ref} \cdot \left( \frac{\dot{m}_{cold}}{\dot{m}_{cold,ref}} \right)^{\Delta p\_exp}$$

Where  $\Delta p$  is limited to  $2 \cdot \Delta p_{ref}$ .  $\Delta p_{ref}$ ,  $\dot{m}_{cold,ref}$  and  $\Delta p\_exp$  can also be specified by the user

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

MODE	only mode 2 for counter flow is available
UAREF	reference overall heat transfer coefficient
DPREF	reference pressure loss
FLWCREF	reference mass flow cold side
EXP_UA	power law exponent
EXP_DP	power law exponent

##### INPUTS:

THI	inlet temperature hot side
FLWH	mass flow hot side
TCI	inlet temperature cold side
FLWC	mass flow cold side
XCI	cold side quality
PCO	cold side outlet pressure
CPH	hot side specific heat

##### OUTPUTS:

THO	outlet temperature hot side
FLWH	mass flow hot side
TCO	outlet temperature cold side
FLWC	mass flow cold side
QT	heat transfer rate
EFF	effectiveness
XCO	cold side outlet quality
PCI	cold side inlet pressure

### Evaporator (Type 316)

OBJECTIVE: This model simulates a water evaporator, giving outlet temperatures and flow rates of hot and cold streams as well as demanding for a certain water inlet flow rate to obtain total evaporation. The cold side is assumed to be water/steam depending on the xci quality. Water/Steam conditions are given by temperature, pressure and quality. The effectiveness method is used to describe the heat transfer using an overall heat transfer factor UA. UA and the pressure loss is evaluated like the Eco\_SH model.

$$\eta_{Evaporator} = 1 - \exp\left(\frac{-UA}{\dot{m}_{hot} \cdot cp_{hot}}\right)$$

$$Q_{trans} = \eta_{Evaporator} \cdot cp_{hot} \cdot \dot{m}_{hot} \cdot (T_{hot,in} - T_{saturated})$$

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

UAREF	reference overall heat transfer coefficient
BD	blow down fraction
DPREF	reference pressure loss
FLWCREF	reference mass flow cold side
EXP_UA	power law exponent
EXP_DP	power law exponent

##### INPUTS:

THI	inlet temperature hot side
FLHI	mass flow hot side
TCI	inlet temperature cold side
PCO	cold side outlet pressure
XCI	cold side quality
CPH	hot side specific heat

##### OUTPUTS:

THO	outlet temperature hot side
FLHO	mass flow hot side
TCO	outlet temperature cold side
PCI	cold side inlet pressure
XCO	cold side outlet quality
FLCDM	cold side flow rate demand
FLCO	mass flow cold side

Qdot      transferred power  
EFF      effectiveness

### Turbine stage (Type 318)

OBJECTIVE: This turbine stage model calculates the inlet pressure of the turbine stage from the outlet pressure, the steam mass flow rate and reference values of inlet and outlet pressure and mass flow rate using Stodolas law of the ellipse. It evaluates the outlet enthalpy from the inlet enthalpy and inlet and outlet pressure using an isentropic efficiency. This is calculated from a reference value by

$$\eta_{is} = \eta_{is,ref} \cdot (1 + a \cdot f + b \cdot f^2 + c \cdot f^3) \quad \text{limited between 0.2 and 1}$$

with 
$$f = \frac{\dot{m} - \dot{m}_{ref}}{\dot{m}_{ref}} \quad \text{limited between } + - 0.7$$

A bypass indicator output is set to 1 if either the input bypass indicator is equal to one or if the flow rate is below a reference fraction given in the parameters. If the bypass flag is set, the steam passes the turbine without doing any work remaining in the same condition. The pressure is assumed to be the same as under minimal flow conditions when the bypass is turned off.

The turbine stage can be combined with a controlled splitter (type189) in order to assemble an extraction turbine.

### TRNSYS COMPONENT CONFIGURATION:

#### PARAMETERS:

PIREF	reference inlet pressure
POREF	reference outlet pressure
FLREF	reference flow rate
ETAIREF	reference efficiency
ETAG	generator efficiency
alpha	coefficient
beta	coefficient
gamma	coefficient

#### INPUTS:

PO	outlet pressure
FLI	inlet flow rate
HI	inlet enthalpy
BYEI	inlet bypass indicator

OUTPUTS:

PI	inlet pressure
FLO	outlet flow rate
HO	outlet enthalpy
POW	turbine power
BYEO	outlet bypass indicator
ETAI	isentropic efficiency

### Pressure throttle (Type 319)

OBJECTIVE: This component is simply the pressure loss calculation from the turbine stage component separated out. In this way, the pressure loss that should be seen by the throttling valve can be seen in the bypass side during start-up and shutdown. The system can then be properly controlled by the normal operation

$$P_{in} = \sqrt{\left(\frac{\dot{m}_{in}}{\dot{m}_{in,design}}\right)^2 \cdot (P_{in,design}^2 - P_{out,design}^2) + P_{out}^2}$$

### TRNSYS COMPONENT CONFIGURATION:

PARAMETERS:

PIREF	reference inlet pressure
POREF	reference outlet pressure
FLREF	reference flow rate

INPUTS:

PO	outlet pressure
FLI	flow rate
HI	inlet enthalpy

OUTPUTS:

PI	inlet pressure
FLO	flow rate
HO	outlet enthalpy

### **Water/Steam attemporator (Type 304)**

OBJECTIVE: This model describes the mixing of a steam- and a feedwater-flow. For given temperature  $T_1$  and  $T_2$ , flow  $\dot{m}_1$  and  $\dot{m}_2$  and steam quality the outlet temperature  $T_{mix}$  is calculated. For given setpoint temperature  $T_{mix}$  the demanded feedwater flow  $\dot{m}_2$  to achieve  $T_{mix}$  can be calculated by

$$\dot{m}_2 = \dot{m}_1 \cdot \frac{cp_1 \cdot (T_1 - T_{mix})}{cp_2 \cdot (T_{mix} - T_2)}$$

TRNSYS COMPONENT CONFIGURATION:

PARAMETERS: none

INPUTS:

- steam flow rate kg/hr
- steam inlet temperature C
- steam quality -
- feedwater inlet flow rate kg/hr
- feedwater inlet temperature C
- attemp outlet pressure BAR
- setpoint temperature C

OUTPUTS:

- demanded feedwater flow rate kg/hr
- demanded Steam flow rate kg/h
- outlet flow rate kg/hr
- outlet temperature C
- outlet quality -
- inlet steam pressure BAR

### **Thermal capacity (Type 306)**

OBJECTIVE: Thermal capacity is modelled with a lumped capacity model using an energy balance for a mass with capacity  $C$  and initial temperature  $T_0$ , that is heated by a capacity flow rate  $\dot{C}$ , with inlet temperature  $T_{in}$  and overall heat transfer coefficient  $UA_i$ . Convective energy losses of this lumped mass to the ambient with temperature  $T_a$  are considered by the overall loss coefficient  $UA_a$ . The flow outlet temperature  $T_{out}$  and lumped capacity steady state temperature  $T_{ss}$  are calculated. Energy gains (if any) are considered by the heat rate  $Q$ . The energy balance can be solved analytically for the capacity temperature, yielding:

$$(T_C(t) - T_{SS}) = (T_C(0) - T_{SS}) \cdot e^{-t/\tau}$$

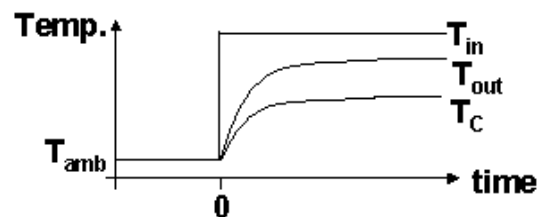
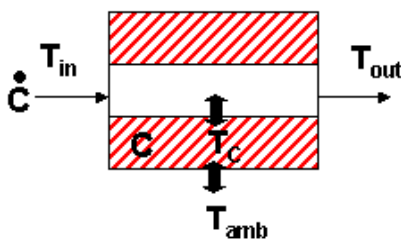
with

$$\tau = \frac{C(UA_i + \dot{C})}{UA_i \dot{C} + UA_i UA_a + UA_a \dot{C}} \quad \text{and}$$

$$T_{SS} = \frac{(\dot{C} + UA_i)Q + (UA_a UA_i + UA_a \dot{C})T_a + (UA_i \dot{C})T_{in}}{UA_i \dot{C} + UA_i UA_a + UA_a \dot{C}}$$

This results in a fluid outlet temperature:

$$T_{fluid,out} = \frac{UA_i \cdot T_C(t) + \dot{C} \cdot T_{fluid,in}}{UA_i + \dot{C}}$$



The coefficients used in this model can be either estimated from the component model for which they are used, or if transient measurement data are available, the parameters can be adjusted to meet the time constant  $\tau$ .

For heat exchanger models, the capacity is linked upstream on the hot side, so that the hot side inlet temperature of the heat exchanger is reduced during start-up and less energy is transferred. An evaporator, for instance, will not demand for a feed water flow as long as the hot side temperature is below the boiling temperature of the water.

TRNSYS COMPONENT CONFIGURATION:

PARAMETERS:

M	mass
CP	specific heat capacity
T	temperature
KA	overall heat transfer coefficient
kA_A	overall loss coefficient

INPUTS:

FL_I	inlet mass flow rate
TF_I	inlet temperature
CP_F	specific heat capacity
T_amb	ambient temperature
Q_dot	power gain

OUTPUTS:

TF_O	fluid outlet temperature
FL_O	fluid outlet flow rate
Tbar	thermal mass temperature

### 3.4 MODELS OF THE SOLAR THERMAL ELECTRIC SUBLIBRARY

#### Parabolic trough (Type 396)

OBJECTIVE: The parabolic trough collector based on the model of Lippke[3], uses an integrated efficiency equation to account for the different fluid temperature at the field inlet and outlet of the collector field. It calculates the demanded mass flow rate of the heat transfer fluid to achieve a user-defined outlet temperature  $T_{out}$  by

$$\dot{M} = \frac{\dot{Q}_{net}}{c_p (T_{out} - T_{in})}$$

using

$$\dot{Q}_{net} = \dot{Q}_{abs} - \dot{Q}_{pipe}$$

and

$$\dot{Q}_{abs} = A_{eff} \cdot DNI \cdot \eta$$

$$\Rightarrow \eta = K \cdot M \cdot Sh \cdot \left[ A + B \cdot \frac{\Delta T_{out} + \Delta T_{in}}{2} + (C + C_w \cdot WS) \cdot \frac{\Delta T_{out} + \Delta T_{in}}{2 \cdot DNI} + D \cdot \frac{\Delta T_{out} \cdot \Delta T_{in} + \frac{1}{3} (\Delta T_{out} - \Delta T_{in})^2}{DNI} \right]$$

This is the absorber efficiency model as presented in [3]. The coefficients A, B, C, Cw and D are empirical factors describing the performance of the collector. They can be found for the SEGS LS-2 collector e.g. in [8]. The factor K is the incident angle modifier, M considers end losses and Sh considers shading of parallel rows. Evaluation of these parameters is described in [3].  $\Delta T_{in,out}$  is the difference between collector inlet or outlet temperature and



ambient temperature and DNI is the direct normal irradiation.  $\dot{Q}_{pipe}$  accounts for losses in the piping and expansion vessel using empirical coefficients.

The model considers also electrical parasitics for tracking, start-up and shutdown as well as for pumping. Shutdown is performed automatically at high wind speeds. A flow rate rampdown period is now included so that the flow rate at the end of the day is linearly decreased to a level (RDRatio) normally higher than the turn-down ratio (TDR) over a specified time period (RDTime). The fraction of field in track can be specified by the user as a control input.

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

- A - Loss coef.
- B - Loss coef.
- C - Loss coef.
- Cw- Loss coef.
- D - Loss coef.
- CR- Clean Reflectivity
- BM- Broken Mirror Fraction
- L - Length of SCA m
- W - Aperture Width of SCA m
- F - Focal Length of SCA m
- RS- Rowspacing m
- Atot- Total Field Area m\*\*2
- Pmax - Pump max power consumption at (Frmax) kJ/h
- FRmax- Pump max flow rate kg/h
- PC1- Pump Power Coeff. 1 kJ/kg
- PC2- Pump Power Coeff. 2 kJ/kg
- PC2- Pump Power Coeff. 3 kJ/kg
- Tank- Tank Heat Loss Rate W
- Pipe- Piping Heat Loss Per Unit Field Area at 343C W/m\*\*2
- Tpar - Tracking Parasitics Per Unit Field Area at 275C W/m\*\*2
- Spar- Stow Parasitics Per Unit Field Area kJ/m2
- WSmax- Wind Speed Limit m/s
- TDR- Turn Down Ratio

##### INPUTS:

- ToD- Demanded Outlet Temperature Solar Field C
- Tin- Inlet Temperature Solar Field C
- Cl - Cleanliness Solar Field
- Cp - Specific Heat HTF kJ/kg.K
- Az - Sun Azimuth (S=0,W=+) degrees
- Zen - Sun Zenith degrees
- DNI- Direct Normal Radiation kJ/h-m\*\*2
- WS - Wind Speed m/s
- Tamb - Ambient Temperature C

Ftrk - Tracking Fraction of Field  
 Favl - Available Fraction of Field  
 TDR- Turn Down Ratio  
 RDTime - Rampdown Time Duration to reach RDRatio\*FRMax hr  
 RDRatio - Rampdown Ratio - Fraction of FRMax to reach after shutdown  
 Greater than TDR

**OUTPUTS:**

FR - Flow Rate Solar Field kg/h  
 Tout - Outlet Temperature Solar Field C  
 Eff - Efficiency Solar Field  
 PARAS - Total Parasitics kJ/h  
 Pdefoc - Power Lost to Defocus kJ/h  
 Pminflo - Power Lost to Min Flow kJ/h  
 Pfluid - Power to HTF fluid kJh  
 ISTATUS - System Status  
     1 = in nightflow mode FR=TDR\*FRmax  
     2 = in on mode with TDR\*FRMAX<FR<RDRatio\*FRMax  
     3 = in on mode with RDRatio\*FRMax<FR<FRMax  
     4 = in shutdown (RDTime and RDRatio applicable)

**Old trough (Type 397)**

This model is the former parabolic trough type 96 from release 1.0. The difference to type 196 is an alternative formulation of the absorber efficiency model. Therefore the empirical coefficients A, B, C, CW, D have different number values.

**Tower receiver (Type 395)**

**OBJECTIVE:** The receiver model is like the trough model in that it provides as output the flow rate required to achieve the outlet temperature set point.

Since our initial heliostat field model, like SOLERGY, is based upon a simple field efficiency table interpolation, only the total power to the receiver is calculated. To find the detailed flux distribution on the receiver, a complex numerical convolution, or ray-trace optical model, must be used. Without detailed flux information, an empirical receiver heat loss model is more appropriate than one based on heat transfer relations at the receiver's surface. In this model, the conductive losses are neglected in the calculation of the net absorbed power,

$$\dot{Q}_{net} = \alpha \dot{Q}_{inc} - \dot{Q}_{conv} - \dot{Q}_{rad}$$

where the subscripts  $_{inc}$ ,  $_{conv}$ , and  $_{rad}$  stand for the incident power, the power losses to convection, and the power losses to radiation. The losses are described by third order polynomials with user-supplied coefficients:

$$\dot{Q}_{conv} = C_0 + C_1V + C_2V^2 + C_3V^3$$

$$\dot{Q}_{rad} = R_0 + R_1\dot{Q}_{inc} + R_2\dot{Q}_{inc}^2 + R_3\dot{Q}_{inc}^3$$

where V is the wind velocity. The user can also specify the turn down ratio- below which the power is discarded. The receiver efficiency,  $\eta = \frac{Q_{net}}{Q_{inc}}$  is also provided as an output.

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

Efficiency

##### INPUTS:

IP = Incident Power kJ/hr  
 TCI = Fluid inlet temperature C  
 FLCI= Fluid inlet flow rate kg/hr  
 PCO = Fluid outlet pressure BAR  
 TS = Temperature set point C  
 CP = Fluid Specific Heat kJ/kg.K

##### OUTPUTS:

FLD = Flow rate demand kg/hr  
 FLCO= Fluid outlet flow rate kg/hr  
 TCO = Fluid outlet temperature C  
 PCI = Fluid inlet pressure BAR

#### **Pressurized air receiver (Type 422)**

**OBJECTIVE:** This type can be used for steady state simulation of a pressurised air receiver. The receiver outlet temperature, pressure and enthalpy are calculated depending on inlet conditions of the air flow and the radiation input. A simple black body radiation model is included to calculate the receiver efficiency.



$$\eta_{rec} = \eta_{opt} - \varepsilon \cdot \sigma \cdot \frac{A_{abs}}{P_{rad}} \cdot \overline{T}_{abs}^{-4},$$

$$\overline{T}_{abs} = 0.5 \cdot (t_{air,in} + t_{air,out}) + 273.15.$$

Other model equations can be included easily. Receiver body and piping heat losses as well as receiver cooling losses can be calculated. The pressure loss depending on temperature, pressure and mass flow can be calculated. Type 222 checks for lower and upper radiation flux limits and has 6 different operation modes when the flux limits are violated:

	11	12	13	- low flux: warning only
	21	22	23	- low flux: bypass
high flux:	warning only	bypass	stop	

TRNSYS COMPONENT CONFIGURATION:

PARAMETERS:

- receiver model - [1;4]
- optical efficiency - [0;1]
- emissivity of absorber - [0;1]
- receiver aperture m^2 [0;10000]
- absorbing fraction - [0;1]
- lower flux limit W/m^2 [0;+Inf]
- upper flux limit W/m^2 [0;+Inf]
- operation mode - [10;30]
- emissivity of hot gas piping - [0;1]
- surface area of piping m^2 [0;+Inf]
- convective loss coeff.of piping kJ/hr.m^2.K [0;+Inf]
- cooling loss factor - [0;1]
- design pressure loss factor - [0;1]
- design inlet pressure BAR [0;+Inf]
- design inlet temperature C [-273.15;+Inf]
- design outlet temperature C [-273.15;+Inf]
- design inlet mass flow kg/hr [0;+Inf]
- electric parasitics W [0;+Inf]

INPUTS:

- air inlet temperature C [-273.15;+Inf]
- air inlet pressure BAR [0;+Inf]
- air inlet enthalpy kJ/kg [-Inf;+Inf]
- air inlet mass flow kg/hr [0;+Inf]
- solar input power kJ/hr [0;+Inf]
- control signal - [0;1]
- ambient temperature C [-273.15;+Inf]

#### OUTPUTS:

air outlet temperature C [-273.15;+Inf]  
 air outlet pressure BAR [0;+Inf]  
 air outlet enthalpy kJ/kg [-Inf;+Inf]  
 air outlet mass flow kg/hr [0;+Inf]  
 net thermal power kJ/hr [-Inf;+Inf]  
 thermal efficiency - [0;1]  
 pressure loss factor1 - [0;1]  
 parasitic power kJ/hr [0;+Inf]  
 operation status - [0;1]  
 flux overload - [0;+Inf]  
 optimum gas mass flow to reach  
 design output temperature m\_opt kg/hr [-inf;inf]

#### Heliostat field (Type 394)

OBJECTIVE: The heliostat field model requires a user-supplied field efficiency matrix to evaluate the field efficiency,  $\eta_{field}$ , as a function of the date and time. The power to the receiver is evaluated by:

$$\dot{Q}_{rec} = A_{field} \cdot \rho_{field} \cdot I \cdot \eta_{field} \cdot \Gamma$$

using total mirror surface  $A_{field}$ , reflectivity  $\rho_{field}$ , direct normal radiation  $I$  and a control parameter  $\Gamma$  describing the fraction of the field in track. The model also considers electrical parasitics for tracking, start-up, and shutdown. Shutdown is performed automatically at high wind speeds.

The efficiency matrix gives the heliostat field efficiency for a number of pairs of solar azimuth and zenith angle. This file is read in and interpolated by the TRNSYS routine data (see manual). The number of solar elevation and azimuth data points must be specified in the parameters of this type. The file has the following format

1. line : list of all solar azimuth data points (e.g. for 3 points -120 0 120) (rising order)
2. line : list of all solar zenith angles (eg. for 3 points 0 45 90) (rising order)

following lines with efficiency data for the solar angle data pairs

(-120,0);(-120,45);...;(120,90) with a maximum of 80 characters per line and minimum of one data point per line. A test printout of the matrix can be found in the list file, when Trnsys is run, which should be checked. Since the original Trnsys data routine is limited to 5 values for the azimuth angles, the file data3.for should be linked to the Trnsys code, which uses

increased limits (30). The matrix is linear interpolated using the inputs of the actual solar azimuth and elevation angle.

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

lufeld = Logical Unit No of Field efficiency input data (File)  
 nel = Number of zenith angle data points in field efficiency file  
 naz = Number of azimuth angle data points in field efficiency file  
 nhel = Number of Heliostats  
 fmirror = Mirror Surface per heliostat (m<sup>2</sup>)  
 rho<sub>hel</sub> = Reflectivity of heliostat  
 qstart = Electric work for Startup of one heliostat (KJ)  
 prun = Electric power for tracking one heliostat (kJ/h)  
 vmax = Maximum tolerable wind speed (m/h)

##### INPUTS:

DNI = Direct Norml Insulation (kJ/hm<sup>2</sup>)  
 vwind = Wind Speed (m/h )  
 gamma = Control Parameter ( 0= Field off, 0.5 = 50% of Field focussing, 1.0  
 Total field working)  
 theta = Solar zenith angle (is delivered by Standard trnsys type 16 'Solar  
 radiation Processor')  
 phi = Solar azimuth (is delivered by Standard trnsys type 16 'Solar Radiation  
 Processor')

##### OUTPUTS:

PTR = Power to receiver (kJ/h)  
 PDEFOC = Power which was defocussed due to control constraints or wind  
 speed (Gamma<1) (kJ/h)  
 PPARASi = Parasitic power for tracking (kJ/h)  
 etafeld = field efficiency

## 3.5 MODELS OF THE STORAGE SUBLIBRARY

### Concrete/Oil thermal storage (Type 430)

OBJECTIVE: This model describes a concrete thermal storage for single phase fluid (HTF oil, water). It consists of parallel equally spaced tubes in concrete with HTF flowing through in two possible directions :

flow down (normally charge flow entering hot)  
 flow up (normally discharge flow entering cold).

The main difference to Standard TRNSYS Type10 Rockbed is the three node temperature model: fluid temperature - concrete temperature - ambient temperature.

The model includes thermal capacity of concrete mass, thermal capacity of HTF and thermal loss of concrete to environment. It does not include thermal capacity of (steel) pipe in concrete. Convective and conductive heat transfer perpendicular to flow direction are considered. Axial conduction are not included.

The number of nodes in flow direction can be chosen deliberately (10 nodes are normally sufficient).

#### TRNSYS COMPONENT CONFIGURATION:

##### PARAMETERS:

- HTF specific heat
- HTF density
- total cross sec. area of pipes
- length of storage
- concrete specific heat
- concrete total mass
- reference overall heat transfer coefficient
- overall loss coefficient
- number of nodes
- reference flow rate
- $ak_0 - ak_5$  -5 Parameters for scaling of heat transfer coefficient as:

$$\frac{UA}{UA_{ref}} = ak_0 + ak_1 \cdot \frac{\dot{m}}{\dot{m}_{ref}} + ak_2 \cdot \left(\frac{\dot{m}}{\dot{m}_{ref}}\right)^2 + ak_3 \cdot \left(\frac{\dot{m}}{\dot{m}_{ref}}\right)^3 + ak_4 \cdot \left(\frac{\dot{m}}{\dot{m}_{ref}}\right)^4 + ak_5 \cdot \left(\frac{\dot{m}}{\dot{m}_{ref}}\right)^5$$

##### INPUTS:

- HTF temperature entering on top
- HTF flow rate entering on top
- HTF temperature entering at bottom
- HTF flow rate entering at bottom
- ambient temperature

##### OUTPUTS:

- HTF temperature at bottom
- HTF flow down
- HTF temperature on top
- HTF flow up
- concrete mean temperature
- total energy stored since simulation start
- concrete temperature on top
- concrete temperature in middle node
- concrete temperature on bottom



SolarPACES



heat power to storage  
heat power to fluid  
heat stored  
heat loss

### **Rockbed thermal storage Type 502**

This model is based on standard TRNSYS type 10 with added losses from the roof and the floor of the tank, as well as the thermal inertia caused by concrete foundation of the storage; refer to [9] for details and validation;

### **STOCO Type 431**

Simple routine for charge and discharge control of storage models.



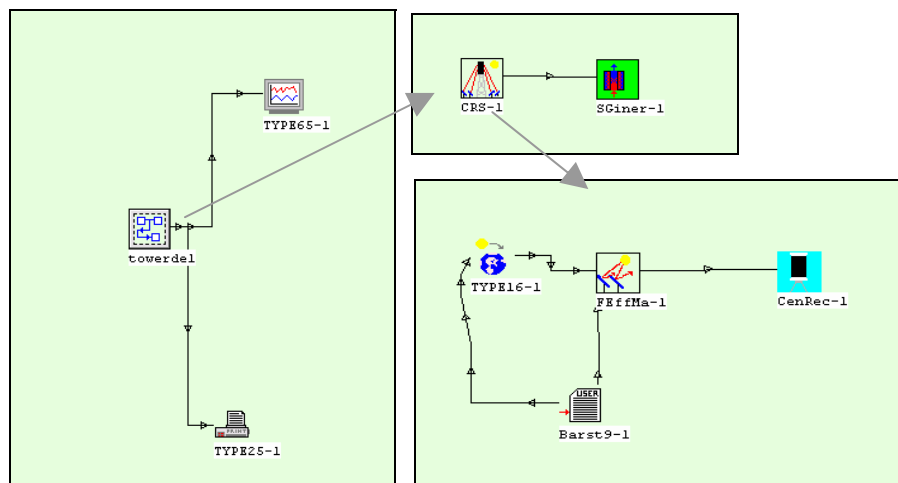
## 4 EXAMPLE APPLICATIONS

Some example applications are provided within the example project folder:

1. A central receiver system (without power cycle) called 'stec\_crs.tpf'
2. A parabolic trough system with steam generator called 'stec\_dcs.tpf'
3. A parabolic trough plus concrete thermal storage system called 'stec\_storage.tpf'
4. A steady state Rankine cycle called 'stec\_cyc.tpf'
5. A solar-fossil hybrid Brayton cycle called stec\_solargt.tpf

There are no limitations regarding the combination of the solar system with the Rankine cycle or thermal energy storage components. However, these simple examples have been selected, because they demonstrate the application of the developed components without being too complex.

## 4.1 CENTRAL RECEIVER SYSTEM



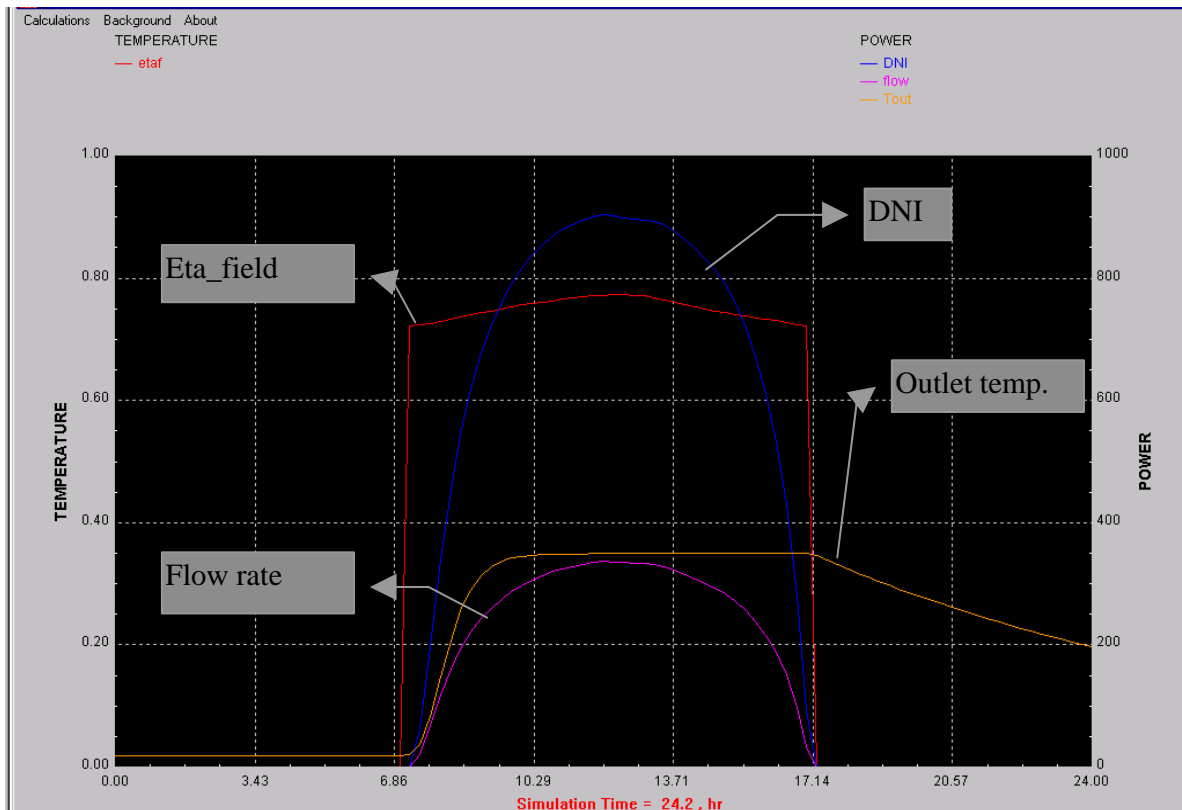
**Figure 4 : Set-up of central receiver system in the Simulation Studio**

In this example, the macro feature is widely used. The first window (figure 4, left side) shows the central receiver set-up as a macro icon ('towersystem') that is linked to two output components: type 25-1 is a standard TRNSYS printer routine that prints the connected information to a data file and Type65-1 is the standard TRNSYS component which plots the connected quantities online (during the simulation runs) to the screen (see figure 5).

The 'towerdel'-macro (top-right) consists of another macro module named 'CRS-1' and the STEC model for the thermal capacity. As explained in section 3.8, the thermal capacity model can be linked to each component to consider capacity effects. In this case the receiver outlet flow and outlet temperature is linked to the inlet flow and temperature of the capacity model.

The 'CRS-1' macro itself consists of 4 basic components: the TRNSYS standard data file reader 'Barst9-1', the standard TRNSYS radiation processor 'type16-1', the field efficiency model 'FEffMa-1' and the Central Receiver model 'CenRec-1'. The links between these components are the direct normal radiation and wind speed from the data reader to the field efficiency model, the solar zenith and azimuth angle from the radiation processor to the field efficiency model and the power from the field efficiency model to the central receiver. The radiation processor additionally requires radiation data to evaluate azimuth and elevation angle. This processor is also able to calculate Direct Normal Insolation data from global and diffuse radiation data.

Part of the output of the calculation for one day is presented in figure 5. It shows the field efficiency, the direct normal insolation (in  $\text{kJ/m}^2\text{h}$ ), the receiver flow rate to meet the setpoint temperature and the outlet temperature of the thermal capacity model, which is used in this case to describe the start-up and shutdown characteristic of the receiver.

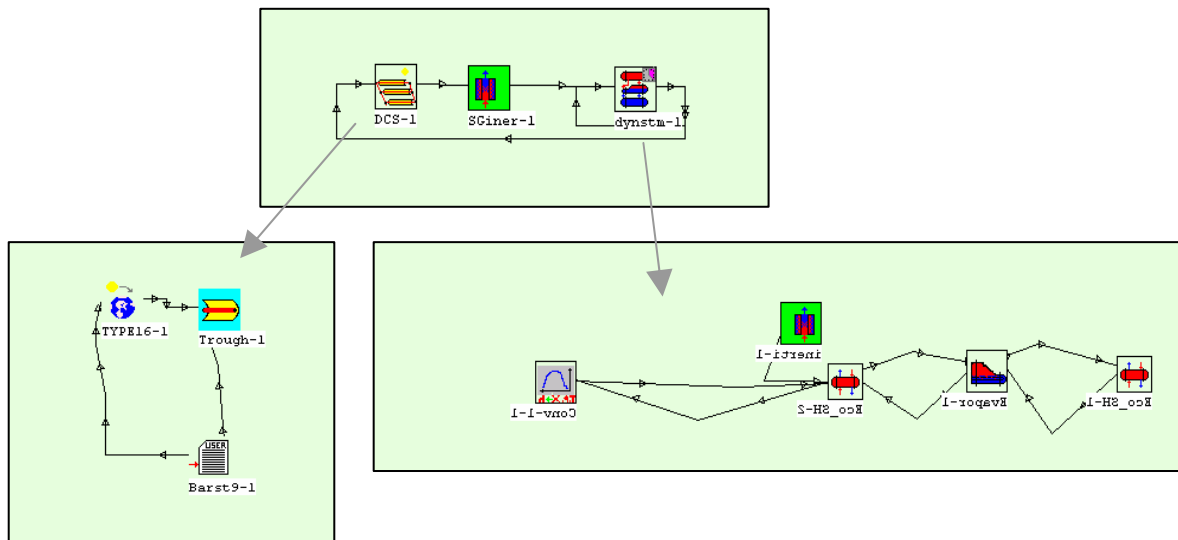


**Figure 5: Output of the Online Plot component Type 65 during a 1 day simulation of the central receiver system**

The outlet temperature of the receiver is still high when the DNI dropped to zero, because the flow rate is zero, so that the temperature reflects the thermal capacity of the receiver mass.

## 4.2 PARABOLIC TROUGH SYSTEM WITH STEAM GENERATOR

The assembly of the parabolic trough project is shown in figure 6. It consists three icons (figure 6 top) representing the macro model for the parabolic trough field (DCS-1), the thermal capacity model and the macro icon of the steam generator (dynsteam-1).



**Figure 6 : Set-up of the trough system with steam generator in the IISibat environment**

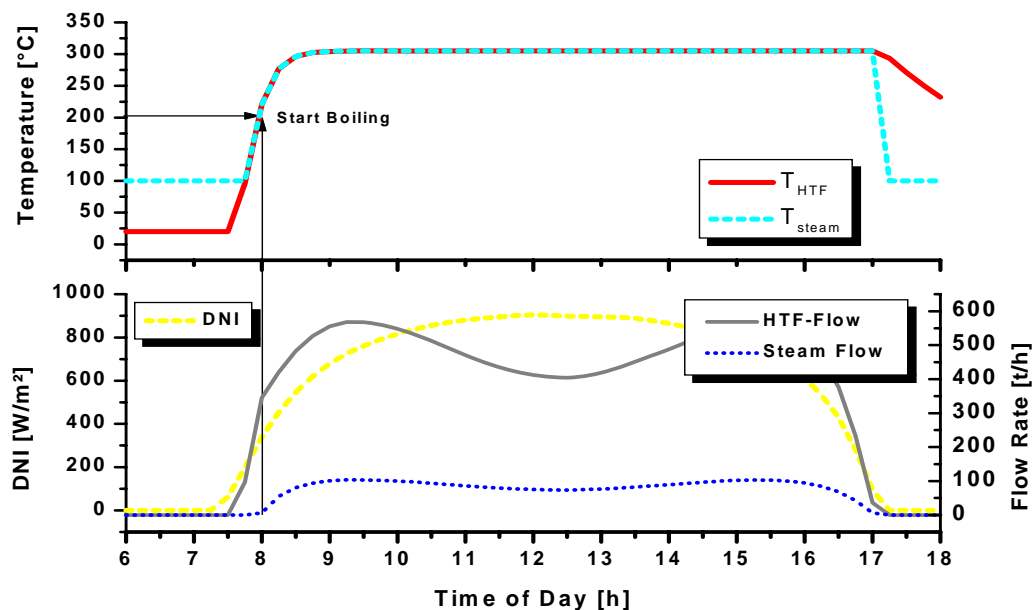
The DCS-1 macro is similar to the CRS-1 macro in the example discussed above. It consists of the standard TRNSYS data reader component (Barst9-1), the standard TRNSYS radiation processor and the STEC Parabolic trough model. The steam generator macro consists of the STEC model of the economiser heat exchanger (ECO-SH-1) , evaporator heat exchanger (Evapor-1), the superheater heat exchanger (ECO-SH-2) and a thermal capacity model (inerti-1).

The links between the components consider two fluid circuits: The heat transfer fluid (HTF) , which is circulated through the trough and the steam generator, and the water steam circuit which has an open end at the feed water of the economiser inlet and an open end at the steam conversion utility function output in this example. The quantities which need to be linked depend on the circuit in the system. In the HTF fluid circuit, temperature and mass flow rate are connected from the output of the component (in flow direction) to the input of the next component. The pressure is not considered as information here. In the water/steam circuit, additionally the quality and pressure are used. In the turbine models, enthalpy is used instead of temperature and quality. These quantities are also connected in the flow direction.

In contrast to that, the pressure information is connected opposite the flow direction: i.e. the pressure information travels from the flow inlet side of one component to the flow outlet side of its upstream component. This approach significantly improves the numerical convergence of the model.

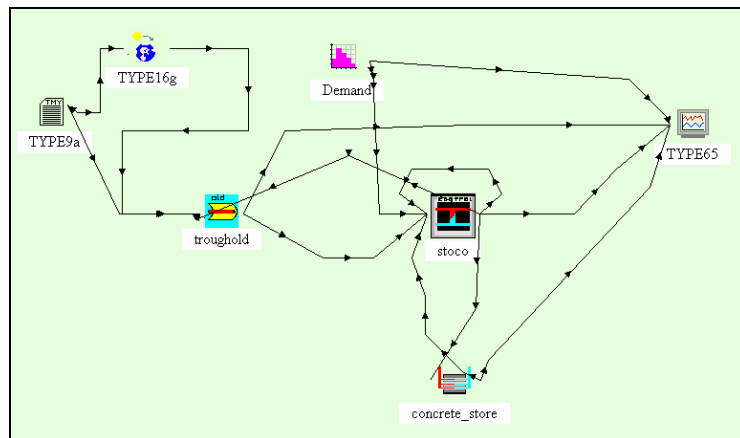
The HTF mass flow rate is determined in this example by the parabolic trough model, in order to meet the temperature set-point condition. The steam flow rate results from the HTF flow rate, HTF outlet temperature and the heat exchanger characteristics. The evaporator model demands for a the according feed water flow rate. This demand signal is linked directly to the economiser inlet flow input in this example. It could also be linked to a pump model which would have the additional impact that the power consumption for the pump and the limitation to a maximum flow rate would be considered also.

The influence of the thermal capacity models of the solar field and of the steam generator can be seen from the calculations results for a clear day operation as presented in figure 7. The HTF temperature is rising later than the direct normal insolation (DNI) due to the capacity of the capacity components. The evaporator model starts to demand for steam flow after the HTF has reached the boiling temperature of the water at the respective system pressure. Therefore, a time delay for the collector outlet temperature relative to the solar insolation as well as a delay of the steam production relative to the collector operation can be simulated achieved by the models.



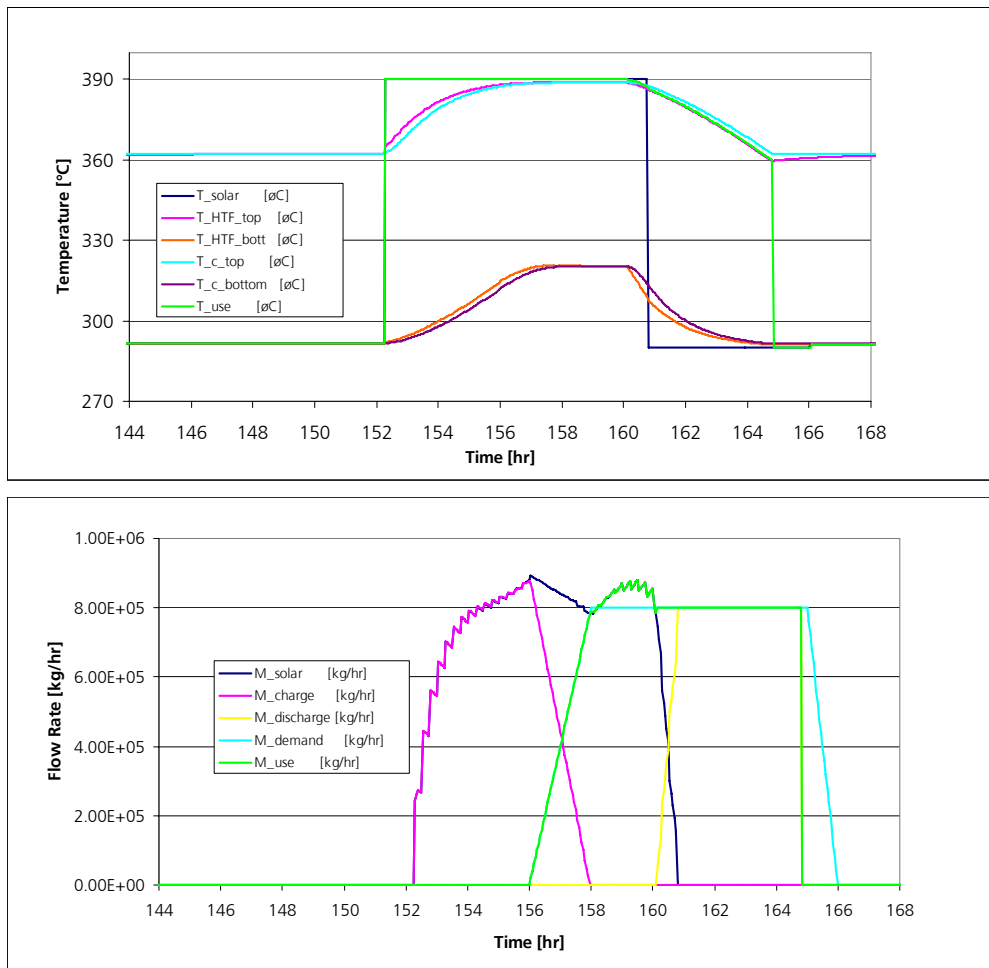
*Figure 7: Results from a 1 day calculation of the trough system with steam generator*

### 4.3 TROUGH AND STORAGE COMBINATION



*Figure 8: Setup of trough/storage combination*

Key components of this example are the well known trough model (former type 96, now type 197) and the new model for concrete thermal storage (type 230). A simple charge/discharge controller (type 231) is added, which decides if the demand can be met directly solar or by the storage. Concrete thermal storages exhibit a characteristic temperature profile. They are charged by a hot fluid (here: hot oil from solar field) flowing through parallel pipes in a certain flow direction, heating the surrounding concrete material. While charging, the hot temperature front moves slowly with the flow direction along the storage. When the fluid leaving the storage exceeds a certain temperature limit (here: 320°C) the storage is said to be full and the charging process is stopped. Otherwise the thermal losses in the solar field would rise extremely. Accordingly, the storage is discharged by a cold fluid flowing in the opposite direction and cooling the concrete. When the cold temperature front reaches the end and the hot fluid falls short of a certain lower temperature limit the storage is said to be empty and the discharging process is stopped. Otherwise the efficiency of the demanding unit (e.g. steam cycle) would drop significantly.

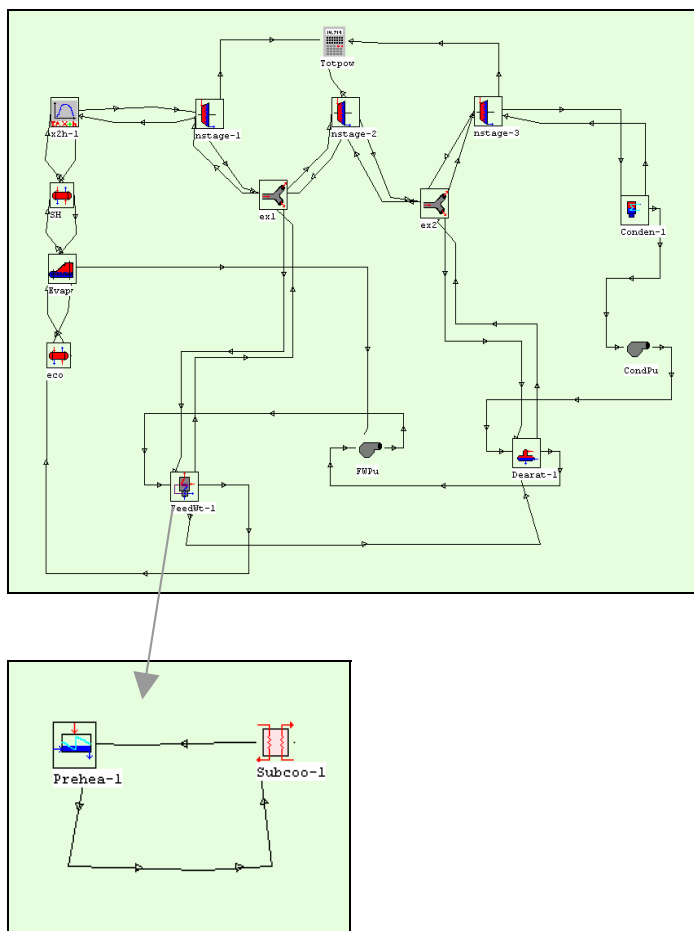


**Figure 9: Results from a 1 day simulation of the trough/storage combined system**

Figure 9 shows the simulation results from day 6 of the included example. There is a time shift between the solar field operation (from about 8:00 to 17:00) and the heat demand (from 12:00 to 22:00). Hence the storage is charged in the morning hours (charge flow: pink line) by the hot HTF from the solar field (390°C dark blue line). The oil and concrete temperatures in the storage increase. The charge flow decreases as the demand rises and stops at 12:00. When the solar flow exceeds the demand (14:00-16:00), the storage cannot be charged as the oil exit temperature has reached the limit of 320°C. When the direct solar heat supply ends (16:30) the storage is discharged (discharge flow: yellow line) until the oil temperature falls below 360°C (at about 21:00). The demand until 22:00 cannot be met in this case.

## 4.4 SIMPLE RANKINE CYCLE

The set-up of the Rankine cycle is shown in Figure 10 and Figure 11. It consists of a boiler section which is similar to the example given above. Down stream of the boiler a steam turbine with two extraction lines is presented by three turbine stage modules (nstage-1, nstage-2, nstage-3) and two extraction splitters (ex1, ex2). A standard TRNSYS calculator utility component (Totpower) is used to add up the mechanical power production of all three stages. The final turbine stage is connected to the condenser module (Conden-1). The two extraction splitters are linked to the deaerator module (dearat-1) and the feedwater heater macro (feedwt-2). This macro consist (as shown in figure 8 lower left side) of a condensing preheater (preheat-1) and a subcooler module (subcool-1). Additionally a condenser pump (CondPu) and a feedwater pump (FWPu) are part of the system.



**Figure 10 : Set-up of the Rankine cycle in the Studio**





The relevant links are discussed in the following:

The evaporator demand flow signal is linked to the control input of the feedwater pump which sets the flow rate of the whole system. The condenser pump model uses the input flow rate as flow demand signal.

Flow rate and enthalpy are connected from turbine stage outlet to splitter and further from the splitter outlet to the turbine stage inlet. The pressure is connected in the opposite direction from condenser to turbine stage outlet to splitter inlet and so on. Pressure and enthalpy are connected from the second splitter outlet to the preheater/deaerator inlet whereas the steam flow rate (demand) is connected in the opposite direction.

The feedwater flow rate and temperature from the condenser outlet is linked first to the pump, then to the deaerator, then to the feedwater pump, then to the preheater and then to the economiser inlet.

The temperature, quality and flow rate of the condensed extraction steam in the condensing preheater is linked to the inlet of the subcooler and further to the condensate inlet of the deaerator.

It is obvious from this example that the set-up of such a system may become rather complex. Therefore it is recommendable to generate macro model for all kinds of subsystems which may be used again later. Thereby, the configuration and all the relevant links of the subsystem is saved and the set-up of new systems can be performed with less effort and a lower probability of making errors.

Inexperienced users should develop a new system model in small steps combining components into subsystems that can be stored as macros. These macros should be individually tested by linking standard TRNSYS input functions (type14) to vary the essential input quantities. The essential output can be connected to the online plotter. After each subsystem macro is checked, the whole system can be set-up by connecting them together.

In order to verify the steady state performance of the components for the Rankine cycle, the commercial Computer Code KPRO [7] was used to evaluate the thermodynamic design performance data of a fictive Rankine cycle as presented in. The results of the TRNSYS code and its deviation from KPRO are presented for temperature, pressure, and mass flow rate at all relevant locations of the plant. ~~For example, TRNSYS found the temperature of the~~

~~steam entering the turbine to be 499.9 C, 0.1 C greater than KPRO predicted.~~ The calculation was based on equal ~~overall hot and cold side~~ heat transfer factors for all heat exchanger units, equal reference pressure losses, and the same inner turbine efficiencies, turbine reference mass flow rates and reference pressures. shows that the conformity of both codes is excellent. ~~For the electrical power output~~ On average, there was a ~~0.6XX~~ % difference between the values computed by each code. -Slight differences may result from different formulations of the property functions. The function used in defined TRNSYS is less precise but much faster than the one used in KPRO. An annual performance calculation ran in less than 5 minutes on a fast PC (0.03 sec/time step) whereas it took more than 10 sec on KPRO for a single run. KPRO itself is neither able to perform calculations over time (e.g. annual runs), nor consider capacity effects and can not be expanded by user components.

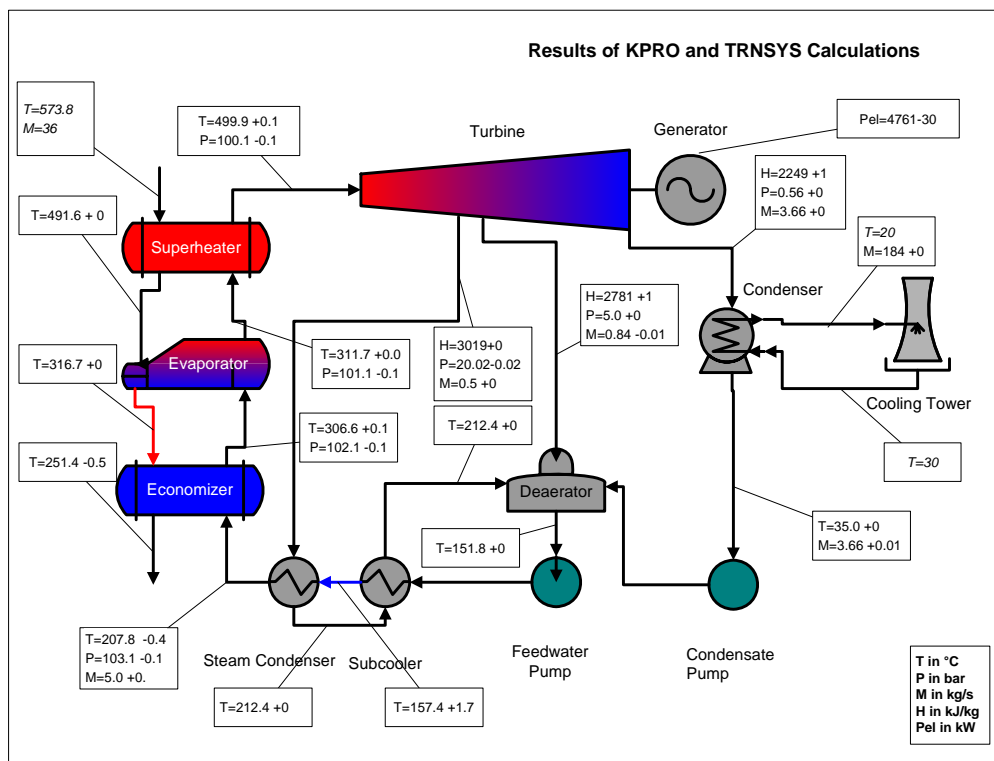
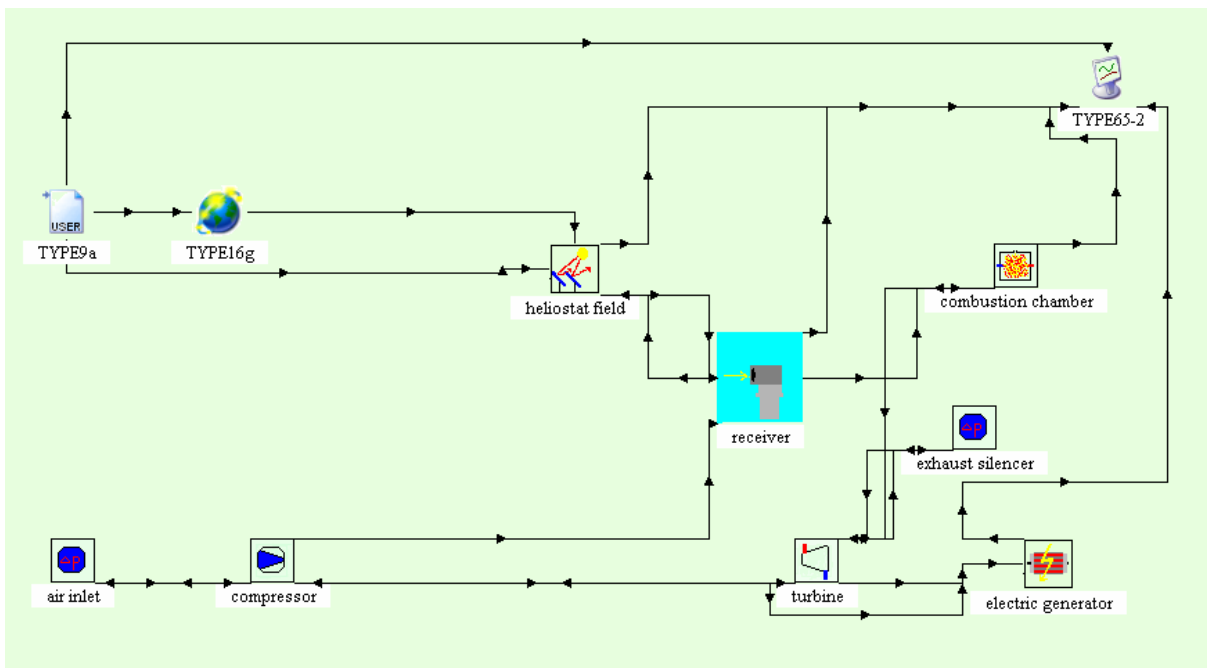


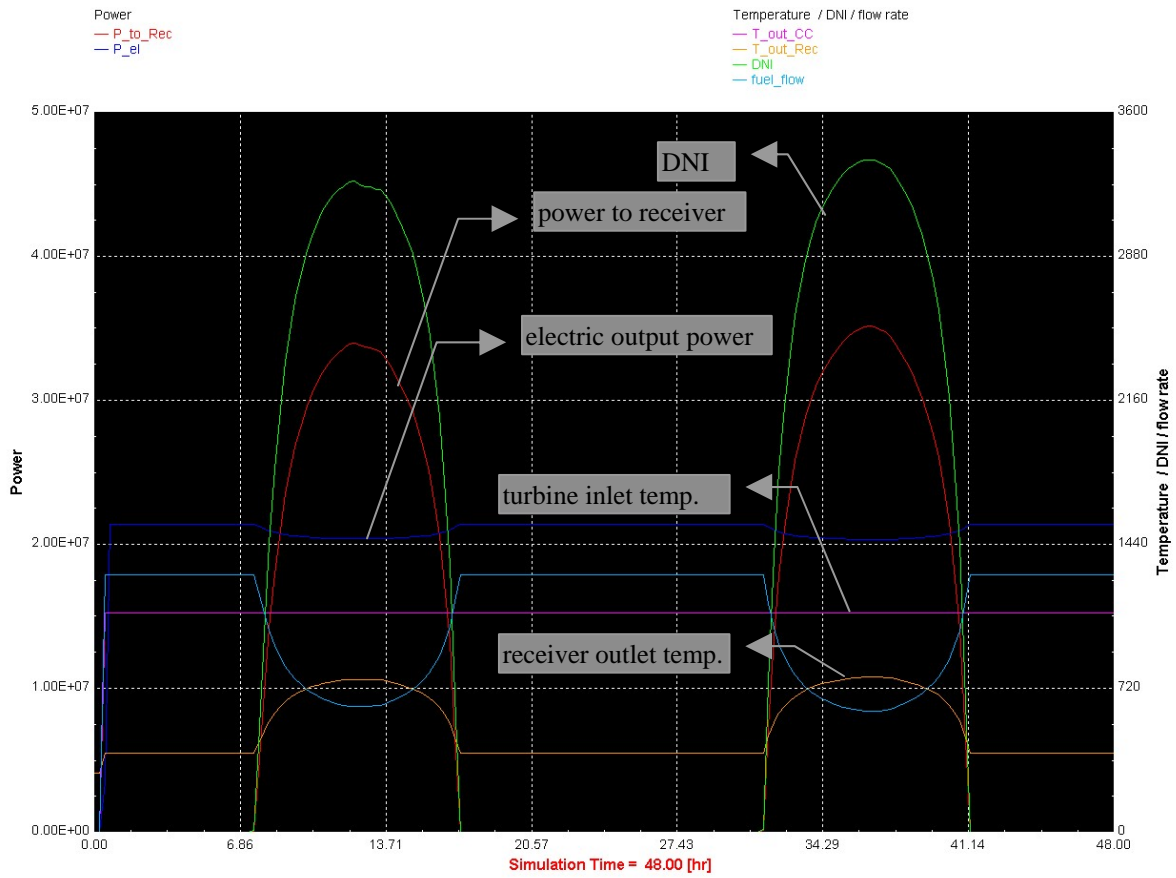
Figure 11: Results from TRNSYS for a fictive Rankine cycle. The sum of both values are KPRO results (italic data are inputs).

## 4.5 SOLAR-FOSSIL HYBRID BRAYTON CYCLE

This example is new with release 2.2 of the STEC library and shows the use of the DLR models from the Brayton sublibrary together with the CRS models. It uses the new pressurised air receiver model (type 222). Figure 12 shows the lisibat set-up of this project. It models a simple Brayton-cycle with a tower receiver acting as a of the pressurised air before it enters the combustion chamber, where the air is heated further to reach the desired turbine inlet temperature . Figure 13 shows an example plot of the system simulation. One can see the receiver heating the air from around 400°C up to almost 800°C depending on the solar input, while the turbine inlet temperature remains constant at 1100°C. Hence, the maximum solar contribution in this fuel saver concept is limited to about 60%. Clearly can be seen the reduced electric output when the solar input in increased. This is due to less total mass flow in the turbine because of the reduced fuel input.



**Figure 12: Screenshot of model-setup for solar hybrid gas turbine (Brayton) cycle.**



**Figure 13: Screenshot example plot for solar hybrid gas turbine (Brayton) cycle.**

## 5 REFERENCES

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- [7] KPRO, Programm zur Berechnung von Kreisprozessen (Simulation Code for the Evaluation of Power Cycles), Vers. 4.1. Fichtner, Stuttgart, 1997.
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- [9] Kolb G.J. and Hassani V.: Performance Analysis of Thermocline Energy Storage proposed for the 1MW Saguaro Solar Trough Plant. Proceedings of ISEC2006, ASME International Solar Energy Conference, July 8-13, 2006, Denver (CO), USA

## Appendix

### A1. System Requirements to use TRNSYS and the STEC Library

The new release 3.0 of the STEC library was designed for the latest updates of TRNSYS 16 and the Simulation Studio. Ask your TRNSYS provider for the appropriate version. The performance of a fast Pentium computer is sufficient in most cases to run annual calculation in a few minutes time.

In order to set-up new models or modify the source code of existing models, a 32 bit Fortran compiler is required which has to rebuild the source code of the models as a 32 bit Windows dynamic link library (dll). The stecdll.dll distributed with this Stec release was built with the Compaq Visual Fortran Version 6.6 Compiler. A lot more information about this topic can be found on the TRNSYS web page (<http://sel.me.wisc.edu/trnsys/Fortran/fortran.htm>).