

Guidance page for practical work 1: modeling of a thermodynamic solar plant

1) Objectives of the practical work

The project objective is to study the operation of thermodynamic solar plants, to show how they can be realistically modeled with Thermoptim.

The practical work is focused on the modeling of a SEGS type solar plant developed by the company Luz, represented as a simple variant of a Rankine cycle, where the boiler is replaced by a steam generator in which the thermal fluid is heated the collector field.

Students are asked to perform an initial setup of the model based on the values provided, and then perform sensitivity studies by varying the flow of thermal fluid and the outlet temperature of solar collectors, considering a constant temperature gap between it and the superheated steam temperature.

This relatively simple practical work is designed for students who have studied already the steam plants. If this is not the case, there should do it first.

This document is an excerpt from the guidance page with complete results, which is reserved for teachers. For this reason, the numbering of figures is flawed.

2) References

Many references on the solar thermal conversion can be obtained from the search engine of the NREL site <http://www.nrel.gov/> (e.g. enter "solar trough" for parabolic collectors, or "solar collector" for flat plate solar collectors).

3) Main practical work

3.1 Question

The TD is based on the technology of parabolic trough used in the Mojave Desert (California - 1984) plant.

In the early 1980s, industrialized countries feared running out of cheap oil and favored those solar systems. The project of the Mojave Desert is one of many solar electric power projects investigated at that time in Spain (Almeria, 1981), France (Targassone), Japan and the former USSR. While these plants have benefited from conditions of sale of electricity of particular interest, economic conditions in the late 1980s put an end to their development.

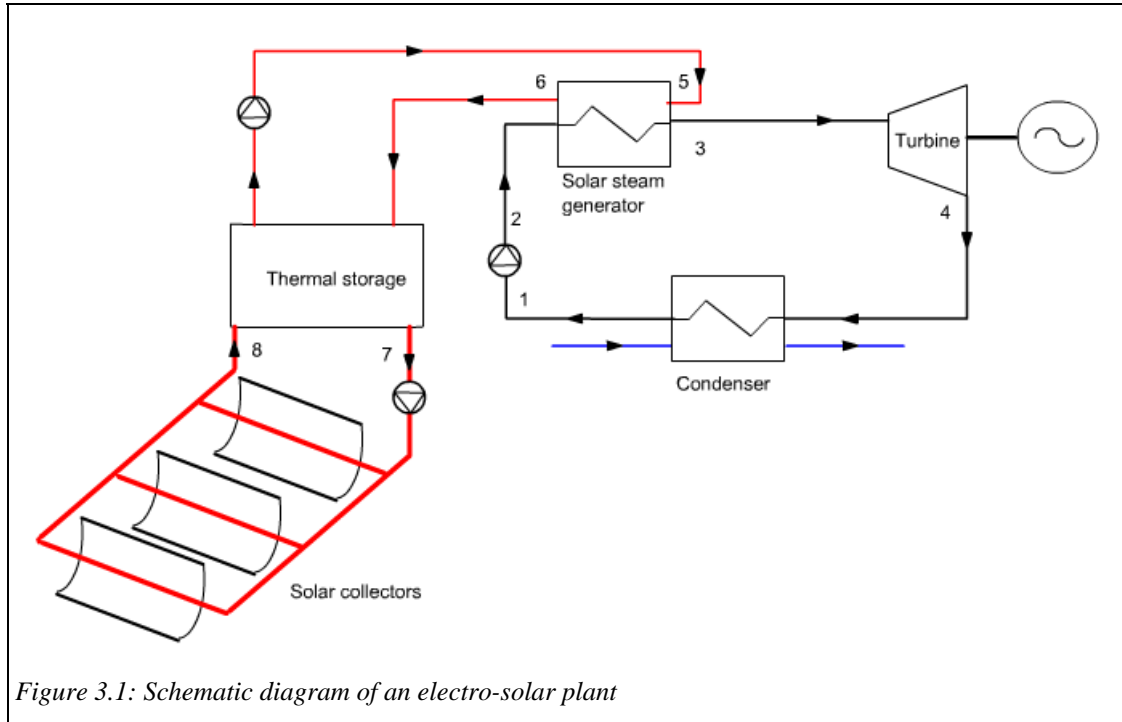
Technology today considered the most mature is parabolic troughs (PT), thanks to the experience in California's Mojave Desert, where 9 plants have been operational since 1984.

Their capacity ranges between 14 and 80 MW, totaling 354 MW. These plants, called Solar Electric Generating Systems (SEGS) were built by the Luz company under an agreement with Southern California Edison Company benefiting from the Public Utility Regulatory Policies Act (PURPA). The particularly appealing electricity sale financial conditions of this agreement being no longer available for new plants, their development stopped since the late 80s.

In SEGS plants (Figure 3.1), the steam gets its heat from a thermal oil heated (at a maximum temperature of 393 °C) by a field of parabolic trough solar collectors. Superheating temperature under these conditions is limited to 371 °C and steam pressure at 100 bar. Moreover, these plants being used in hot, sunny areas, the condensing temperature is relatively high (45 °C, a pressure close of 0.096 bar).

Note that concentrating linear Fresnel reflectors (CLFR) operate at temperatures close to parabolic troughs, so that they could also be used in SEGS plants.

The objective of the work is to study such a cycle and model it with Thermoptim, using the external component "solar concentrator" with the external substance "Dowtherm A" as transfer fluid, and to calculate the efficiency for a incident solar flux of 1000 W/m^2 for a SEGS plant Luz using collectors whose characteristics are given below.



The initial settings will be done on the following basis:

Pressure of the steam cycle: 43.4 bar
 Superheating temperature: $365 \text{ }^\circ\text{C}$
 Condensing temperature: $45 \text{ }^\circ\text{C}$
 Flow-rate of the steam cycle: 35.75 g/s
 Outlet temperature of solar collectors: $390 \text{ }^\circ\text{C}$
 Thermal fluid flow rate: 550 g/s
 Outside temperature: $35 \text{ }^\circ\text{C}$
 Turbine isentropic efficiency: 0.86

3.2 Model of high temperature solar collectors

To reach high temperatures (above $120 \text{ }^\circ\text{C}$), it is necessary to concentrate the sunlight by sets of appropriate reflecting elements (mirrors) or lenses. The main constraint, apart from the cost of the devices higher than flat plate collectors, is the tracking system designed to track the sun in its course. A range of concentrators has been proposed and developed, the choice of parabolic trough corresponding to the best technical and economic compromise for the Mojave Desert power plants.

The solar flux received by the collector is first reflected on the concentrator mirrors and goes then through the glazing material thermally insulating the receiver where it is absorbed by a suitable surface. Reflection, transmission through the glazing and absorption result in optical losses, characterized by an overall transmittivity τ . In high concentration collectors, only the direct component of solar radiation can be directed to the receiver, as the diffuse component cannot be concentrated.

The absorber heats up and loses heat to the outside essentially by radiation and convection. This heat exchange can be characterized by a thermal loss coefficient U . A thermal fluid cools the absorber, taking useful heat that is then transferred or converted for different uses.

The model parameters are:

- glazing transmittivity τ ;
- thermal loss coefficient U ($\text{W}/\text{m}^2/\text{K}$);
- incident solar flux G (W/m^2);
- collector surface A (m^2);
- possibly (if U is referred to this value) the absorber surface S_a (m^2);
- outside temperature T_{out} ($^{\circ}\text{C}$).

The model input data are as follows (provided by other system components):

- the thermal fluid temperature at the collector inlet T_i ($^{\circ}\text{C}$);
- the flow \dot{m} of the thermal fluid (kg/s).

The outputs are:

- the thermal fluid temperature at the collector outlet T_o ($^{\circ}\text{C}$);
- the thermal power received by the thermal fluid Q (W/m^2);
- the collector effectiveness.

Two calculation methods are possible: to determine the outlet point state knowing the collector and absorber surfaces, or determine these surfaces knowing the outlet point state.

The loss coefficient U can often be decomposed into a constant term and a term proportional to the temperature difference between absorber and ambient air: $U = U_0 + U_1 (T_m - T_{\text{out}})$. τ is a function of radiation angle of incidence, mirror reflectivity, absorber absorptivity and transmittance of the glazing protecting the absorber.

With the previous notations, and assuming a linear distribution of temperatures in the collector (the assumption is only valid if the flow is not too low, which is often the case in practice) the model equation is as follows, T_m being the average absorber temperature, and S_c and S_a being respectively the collector and absorber surfaces:

$$Q = \dot{m} C_p (T_o - T_i) = \tau E_s S_c - S_a (U_0 + U_1 (T_m - T_{\text{out}})) (T_m - T_{\text{out}}) \quad (8.2.4)$$

Table 1 gives values of coefficients valid for three types of concentrating collectors, among which are the two parabolic troughs used in Luz SEGS power plants.

TABLE 1 CONCENTRATION COLLECTOR PARAMETERS				
	Luz 2	Luz 3	trough	Fresnel
τ	0.737	0.8	0.7	0.66
S_c/S_a	22.6	26.1	500	20
U_0	-0.0223	-0.0725	0.21	-0.031
U_1	0.000803	0.00089	0.000134	0.00061

The characteristics of the Luz 3 parabolic trough are as follows: area 235 m^2 , width 5 m, length 48 m, receiver consisting of a steel tube 70 mm in diameter covered with a cermet selective coating and surrounded by a vacuum glass tube (with pressure of the order of 0.013 Pa). The absorption coefficient of the selective coating is equal to 0.96 with respect to direct radiation, and its emissivity at $350 \text{ }^{\circ}\text{C}$ is 0.19. Mirrors are made of glass panels, hot shaped, silvered on their posterior surface and protected against external damage. Collectors track the sun by rotating around a north-south axis thanks to hydraulic control.

By dividing the heat collected by the product of the collector surface by the irradiation I received, one can express the efficiency (Figure 3.2) as:

$$\eta = \tau - U \frac{(T_m - T_{\text{ext}})}{I}$$

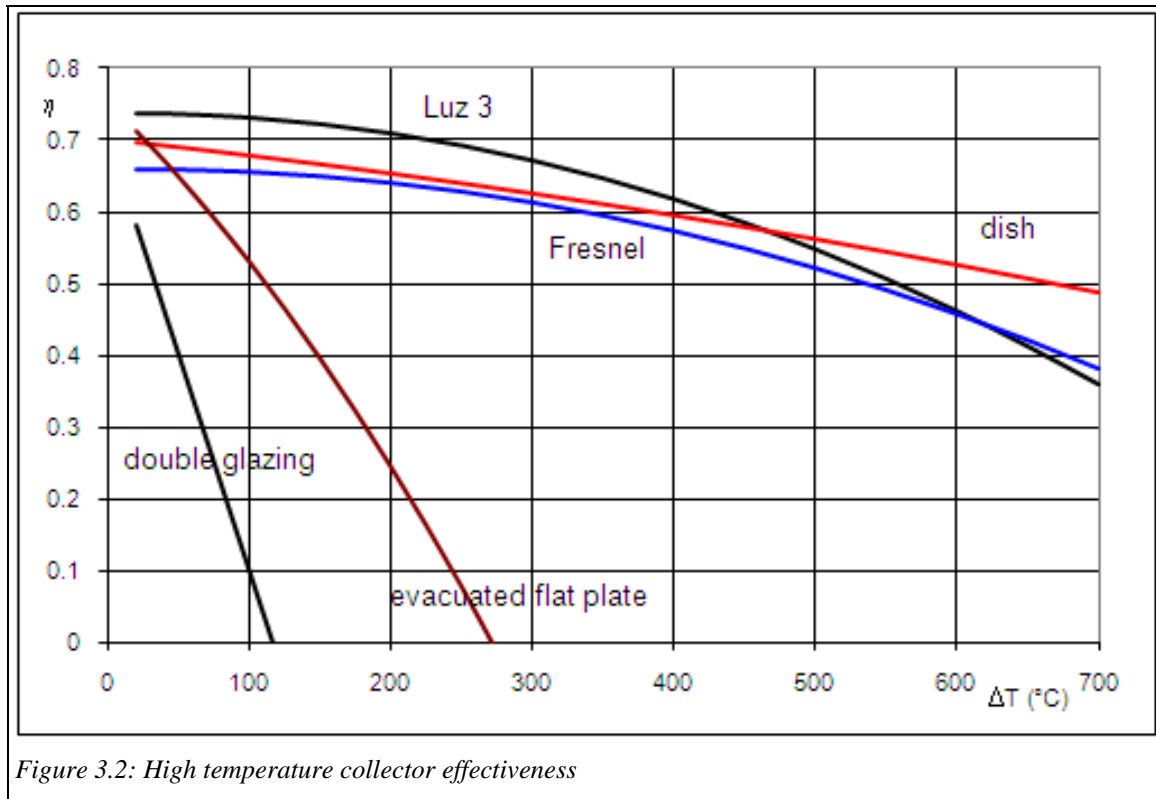


Figure 3.2: High temperature collector effectiveness

3.3 Solving approach

For students to become familiar with the thermodynamic solar energy conversion, it is recommended that they begin by studying the first 20 steps of Diapason session ENR01En. They can then do a personal search on the Internet on SEGS plants and further modeling of concentrating collectors trying to understand section 3.2.

They can then start building the model requested. Modeling the SEGS plant cycle in Thermoptim leads to a diagram like the one in Figure 3.3, where the component "solar collector field" is an external process of type "solar concentrator" in which flows the Dowtherm A.

For students who have already modeled a simple steam cycle (if not, they must begin by working on the S25En and S26En sessions), the only difficulties concern the following:

- selection of component "solar concentrator" and substance "DowTherm A"
- construction and setting of the heat exchanger into three parts

Refer for this to the note « Using external classes » or operate as shown in the first nine steps of the Diapason session S07En_ext¹.

How to solve the second is explained in detail at the end of session S18En² on the thermodynamics of heat exchangers in an exercise where are set exchangers representing a boiler for the steam cycle of session S26En.

The screen of the concentrating collector field is given in Figure 3.4, set with the values for the two Luz collectors. To facilitate the calculations, it is best to select "Calculate collector area" because it helps maintain a constant outlet temperature of the collector field: for the setting chosen, the collector area required will be recalculated regardless of the value of the inlet temperature.

¹ Session S07_ext: http://www.thermoptim.org/SE/seances/S07_ext/seance.html

² Session S18En: <http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/session-s18en>

The choice of useful and purchased energy is as usually in ThermoOptim, the collector field being of the second type, and the pump and the turbine of the first type.

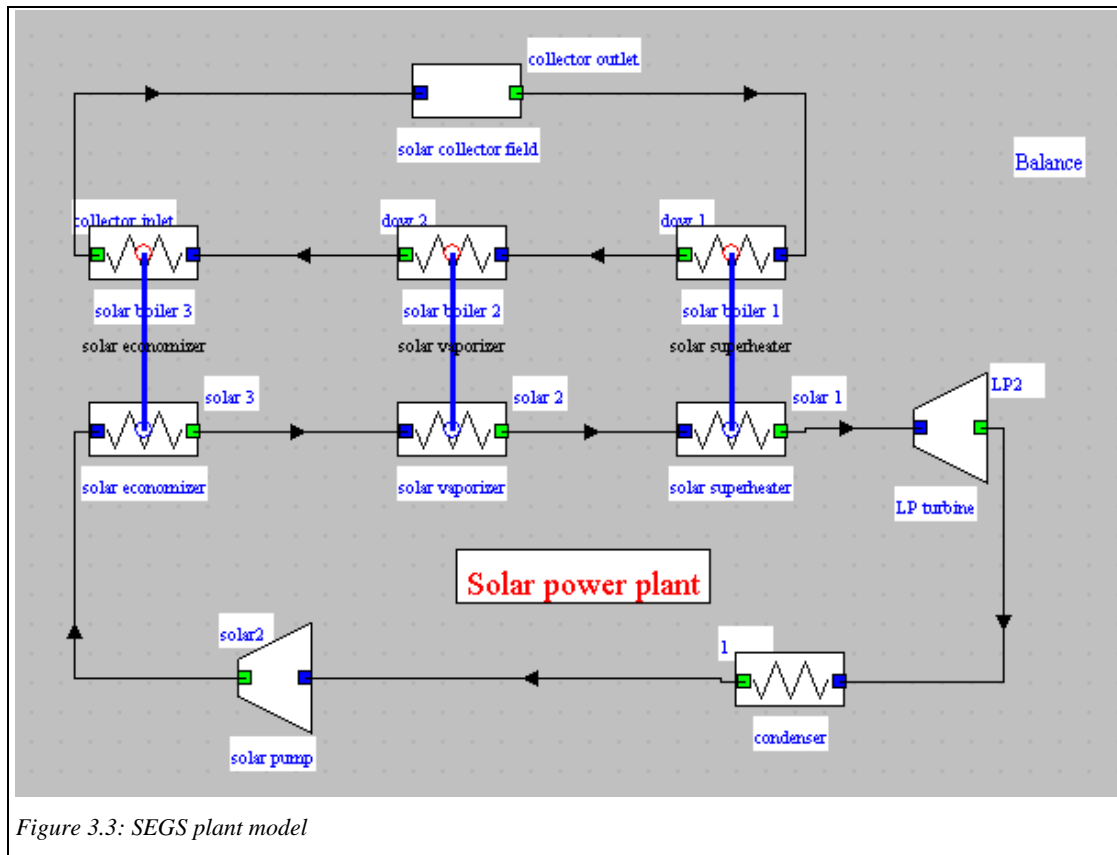


Figure 3.3: SEGS plant model

3.4 Plot in the thermodynamic charts

Once the cycle points determined, it is possible to plot them in a thermodynamic chart such as the entropy chart or the (h, P) chart using the features offered by ThermoOptim.

Figure 3.6 shows the result. A comparison with a flame steam power plant or with the Carnot cycle can then be made.

3.5 Sensitivity studies

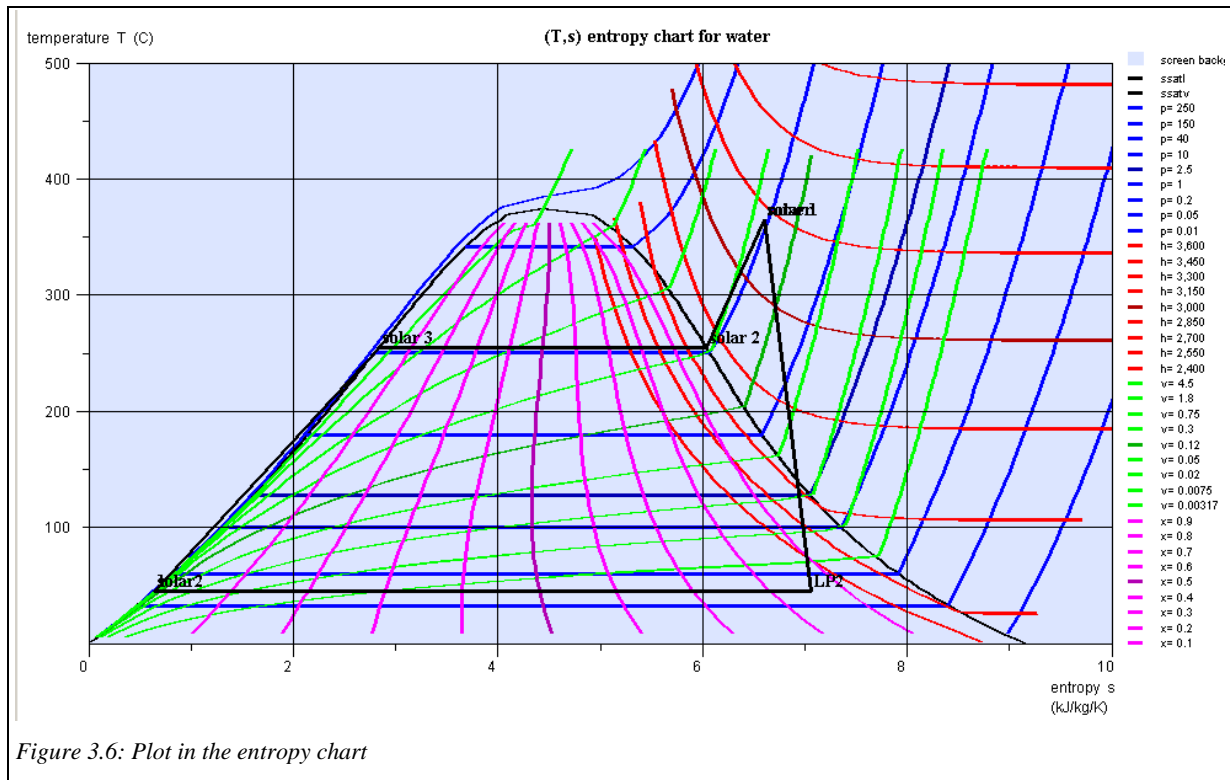
Once the model is built and set, many sensitivity studies can be performed by the students. Particular, they can play on the flow-rate of the thermal fluid, the outlet temperature of the collector field (keeping a constant gap with the superheating of the steam), the pressure of the steam cycle, the type of solar collector...

3.6 Technological design

A possible activity if students have sufficient time is to ask them to calculate orders of magnitude of system sizing (sections of passage ...), to estimate the pressure drops in heat exchangers, and refine the model accordingly.

4) Variants

We propose a few variants, but many others can be imagined, depending on the time available, the level of the students, their number, and educational objectives pursued.



4.1 Model with backup boiler

As we have done, it is quite possible to simplify things by first not including a backup boiler in the absence of irradiation, but it still seems desirable from an educational point of view that students are aware of the need to provide one for a solar power plant.

As the temperature limit of the backup boiler is not as low as that of the solar circuit, it is possible to provide a first expansion in a high pressure turbine, as shown in Figure 4.1.

The only difficulty here concerns the creation and configuration of the divider and the mixer to create the auxiliary circuit. To solve it, just keep in mind that the nodes do not propagate automatically point names and substances in the diagram. You must therefore take care to enter this information in the input tabs of processes located just downstream of the divider and the mixer. For the divider, the point is naturally the same as that downstream of the main process. For the mixer, You must of course create a new point whose substance is water as it flows in the two upstream branches. The pressure must be set by the modeler, equal to the pressure upstream and the temperature will be recalculated by Thermoptim

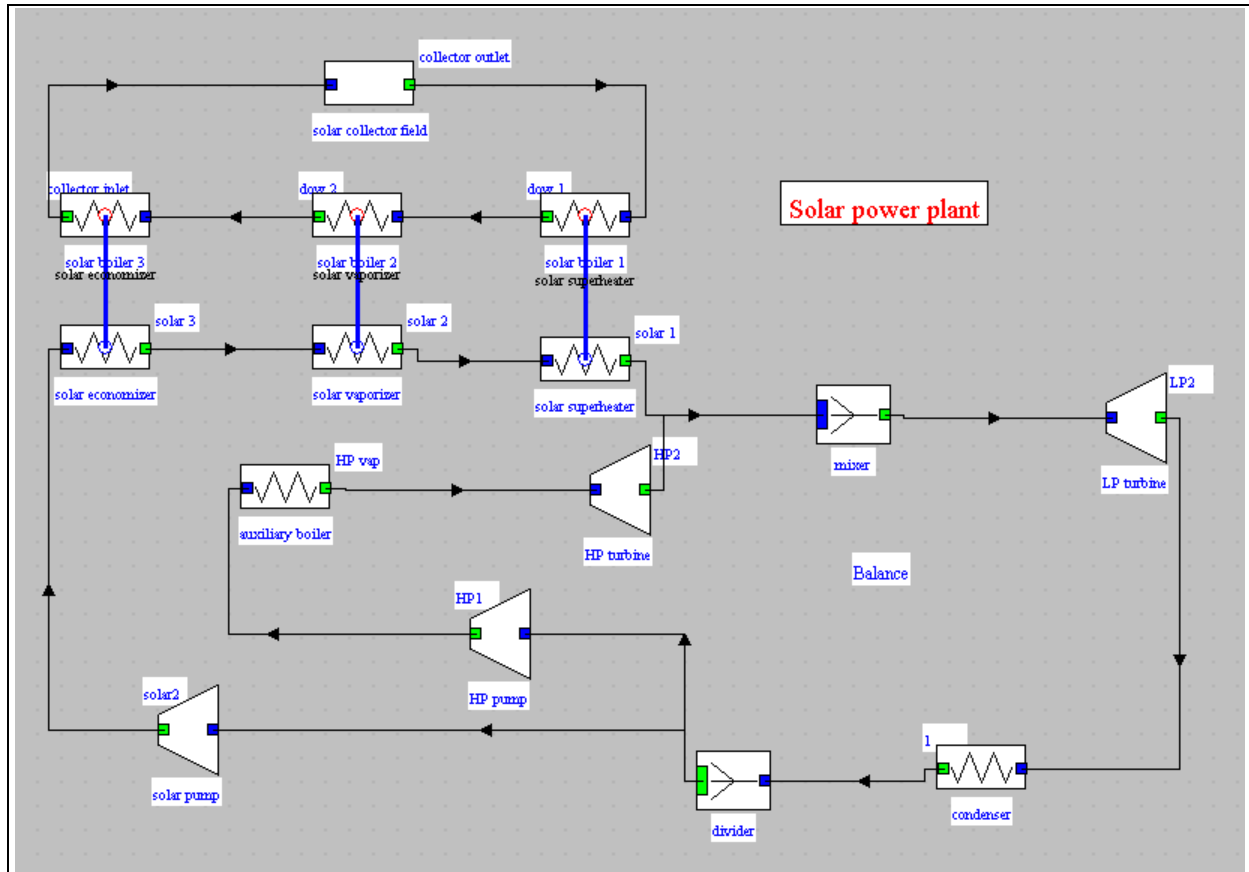


Figure 4.1: SEGS model with backup

Once this model built, students can find a reasonable setting of the backup and compare the efficiencies of solar cycle mode and backup mode. It may be interesting to have them consider the implications of the mode change in the technology sizing, particularly in terms of free flow areas for fluids

4.2 Taking into account an extraction and reheat

Following session S27En³ which show how to model and a set steam power plant cycle with reheat and extraction, students may introduce an extraction in the cycle studied, and compare the new performance with those of cycles without backup or extraction.

4.3 More accurate model of solar concentration collector

Another possible activity is to ask students to develop a model of solar concentration collector more accurate than that used, based on the assumption that heat loss based on the difference between the mean temperature of the fluid in the collector and outside temperature.

For this, they will consider a differential model where the above hypothesis is valid locally. The integration of the equations is not a major problem but must be done properly.

It then becomes possible to ask them to change the external class, but this requires a large time investment on their part to master the relevant techniques, which are explained in Diapason session S07_ext.

³ Session S27En: <http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/session-s27en-extraction>

4.4 State of the art of solar energy thermal conversion technology

If the goal is that students increase their knowledge on solar energy, it is possible to ask them to make a brief state of the art of technologies used for the thermodynamic conversion of solar energy, based on the existing literature, rather abundant.

4.5 Optimization of the collector temperature

To optimize the cycle, a compromise must be found between the superheating temperature and effectiveness of solar collection. The latter is a decreasing function of the average temperature in the collector, while the maximum exergy of water vapor is an increasing function of steam temperature.

You should check by a global reasoning that for a Luz SEGS plant using collectors whose characteristics are given above, the operating temperature is close to the technologically realistic values indicated in the question.

4.6 Cycle exergy balance

Finally, it is possible to ask students to build up the cycle exergy balance, if they have enough time.

Diapason session S06En⁴ will provide necessary explanations on how to proceed.

5) Work files, recommendations

5.1 Work files

The following work files are attached in the archive SEGS.zip:

- code of external classes "solar concentrator" and "Dowtherm A"
- extUser.zip file containing external classes
- Project and diagram files of the ThermoOptim model of the solar plant without backup
- Project and diagram files of the ThermoOptim model of the solar plant with backup

5.2 Recommendations

It is necessary that the teacher checks that students have at their disposal in their work environment ThermoOptim external classes they need.

The easiest way to this is to run ThermoOptim, then open the external class viewer (menu Special of the simulator). Classes being grouped by type, Dowtherm A must appear among the substances, and the "solar concentrator" among the processes, as shown in Figure 5.1

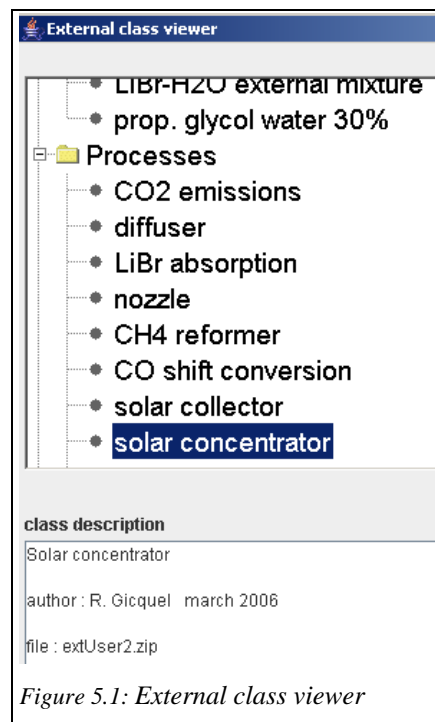


Figure 5.1: External class viewer

If a class is missing, replace the extUser.zip file by that provided in the archive SEGS.zip. If present, it is unnecessary to make this change.

⁴ Session S06En: <http://www.thermooptim.org/sections/enseignement/cours-en-ligne/seances-diapason/s06en-exergy-balances>