

Renewable Energy: Solar Thermal Exercise

In this exercise you will design a concentrating solar power plant and apply basic knowledge in thermodynamics and solar energy conversion technologies.

The Rankine cycle-based power plant Gemasolar was built in Fuentes de Andalucía (Sevilla) in 2011 and is the first of its kind commercially operated. The plant applies the technologies of a central tower receiver and molten salt heat storage. The heat storage permits continuous turbine operation at the rated capacity even after sunset or when there is a reduction in solar radiation due to clouds. Thus, the plant supplies clean and safe base-load power to 25'000 homes. We will use the attached fact sheet to estimate the key figures of the Gemasolar plant.

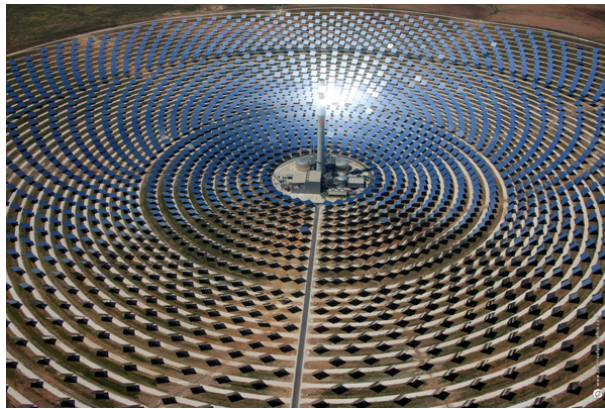


Figure 1: Photo of the Gemasolar power plant (torresolenergy.com).

1. Power block:

- Calculate the rated power of the steam turbine to supply the equivalent of the energy demand of 25'000 homes.
- Calculate pressure, temperature, and enthalpy at each state of the Rankine cycle.
- Calculate the mass flow rate of the water.

Assumptions:

- Annual domestic electrical demand in Spain: 5'100 kWh/household.
- 0.5 MW of the generated electricity is internally used (pumps, control of heliostat field etc.).
- No pressure drop or heat loss through the connecting lines.

2. Storage:

- (a) Calculate the net thermal heat flux required from the molten salt tank to run the turbine at the rated power.
- (b) Calculate the mass flow of the molten salt from the hot to the cold storage.
- (c) Calculate the thermal storage capacity (equivalent hours of turbine operation).

Assumption:

- Adiabatic storage tanks.

3. Solar tower and field:

- (a) Calculate the total heat absorbed by the receiver during an average day in Spain in June.
- (b) Calculate the total reflective area of the heliostat field.
- (c) Calculate the total number of heliostats needed.

Assumption:

- Solar receiver: blackbody, perfectly insulated (no convection/conduction losses).

4. Efficiency:

- (a) Calculate the thermal-to-electric efficiency for a day in June with continuous 24h baseload supply.
- (b) Calculate the overall efficiency for a day in June with continuous 24h baseload supply (solar energy to electricity supplied to the grid).

5. Emission mitigation:

- (a) Calculate the annual electricity generation.
- (b) Calculate the annual CO₂ mitigation potential of the solar powered Rankine-cycle compared to a conventional combined cycle power plant with 50% efficiency.
- (c) Calculate the annual CO₂ mitigation potential of the solar powered Rankine-cycle compared to the standard electrical network mix in Spain.

Assumptions:

- Heating value of natural gas: 47 MJ/kg.
- Consider a complete combustion via $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$.
- The CO₂ emissions of the electrical network mix in Spain is estimated by 300 g_{CO₂}/kWh.

6. Parameter variation:

Use Matlab's XSteam function <http://www.mathworks.com/matlabcentral/fileexchange/9817-x-steam-thermodynamic-properties-of-water-and-steam> and implement the above cycle with storage in Matlab. As an engineer in charge of implementing a new Rankine cycle-based solar power plant, your task is to know if there are possibilities to increase the storage capacity by modifying different operating conditions such as:

- (a) The turbine inlet pressure: varying between 70-250 bar.
- (b) The turbine inlet temperature: varying between 400-750 °C.
- (c) The power block outlet steam quality: varying between 85% and 95%.
- (d) The condenser outlet temperature: varying between 290 K and 322 K.

Plot these four different cases and comment.

Hint: Copy the m-file "XSteam.m" in your current MATLAB directory. The following syntax allows for evaluating steam properties: $h = \text{XSteam}('h_pT', p, T)$. Three arguments are required, first, a string ('h_pT') indicating which quantity you want to compute based on which two other quantities, and the other two quantities (p,T). The input units are: °C, bar, kJ/kg, kJ/(kg.m) and m³/kg. A full list of possible strings as first arguments are given in the file "XSteam.m", relevant for the exercise are: h_pT, T_ph, hL_p, Tsat_p, vL_p, where h is specific enthalpy, L after parameter means saturated liquid and V saturated vapor, T is temperature, and p is pressure. The supplement sat can be used after T or p to evaluate saturation temperature or pressure. Note that when evaluating properties at saturation only one value will be required (e.g. Tsat_p or vL_p).