Thermodynamic analysis of a concentrated solar energy desalination plant

Piotr Mazur

piotr.mazur@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

In this paper, a concentrated solar power desalination plant is analysed. Desalination process is a chance to bring fresh water to regions with access only to seawater and the use of solar energy minimises the carbon footprint of this energy intensive process. The aim is to perform a thermodynamic analysis and observe the behaviour of the system with considered location in Saudi Arabia and the Red Sea as the seawater source. A review of available systems is performed resulting in the choice of a solar tower with thermal storage and a multi-effect distillation as a best fit for the requirements of the system. A model for each part of the system is developed based on literature and validated for correct implementation. The entire model is used to perform a simulation of operation over one year. A strong variation of some parameters within hours requires a part of the model to perform calculation on an hourly basis. The results show a high variation of fresh water produced depending on the month, mainly influenced by the temperature of the seawater. The variation of the DNI impacts the amount of solar power collected and requires a large storage tank to allow for a continuous operation of the system. The CSP desalination system is a chance for a fresh water source, but it still has its problems, mainly resulting from the changing weather conditions and large thermal storage tank requirements.

Keywords: concentrated solar power; desalination; system modelling; solar tower; thermal storage; central receiver;

1. Introduction

Water is one of the resources necessary for every human to survive. Unfortunately, for many people access to fresh water is limited. Although water covers up to 70% of the Earth's surface, around 97% of that is salt water in seas and ocean [1]. A way to make use of that salt water is to apply a process of desalination, which removes salt to make the water drinkable. As it is an energy intensive process, to avoid the use of fossil fuels and the emission of greenhouse gases, renewable energy can be used. The regions with limited access to fresh water are often characterised by high solar irradiance, therefore the use of solar energy is recommended. A thermodynamic analysis of a concentrated solar energy desalination plant is performed to observe the possibility of fresh water production. The location of the analysed plant is Saudi Arabia with the Red Sea as the source of seawater. The region is characterised by high solar irradiance, no precipitation and a high energy consumption. The design power of the desalination plant is 2 MW. The computational model of calculations is implemented in Python [2] and a simulation of operation over one year is performed.

2. Review of technologies

The two main parts of the system that require a choice of technology are the concentrated solar power and the desalination. Possible solutions are reviewed with their advantages and disadvantages. For the solar power, there are three options: paraboloid concentrator, Fresnel lens and solar tower. Paraboloid concentrator can be of dish type or trough type. The first is the most mature technology, but it is not very common in modern application, mainly due to high costs and reliability problems. Trough paraboloid concentrator is currently the most widely applied technology. It is well developed and it requires only one-dimensional tracking. On the other hand, it is prone to dust accumulation and, due to its shape, high wind resistance, which may become an issue in Saudi Arabia, where sandstorms are rather frequent. Fresnel lens utilises several flat mirrors instead of a large one, as trough paraboloid concentrators, which avoids the issue of wind resistance and is cheaper than the previous solutions, but has low optical efficiency and is still in development phase. The choice for this system is the solar tower. It is also a mature technology. Although it requires a large area to place all the heliostats, as Saudi Arabia has large desert areas, that is not a significant problem. To allow for continuous operation of the desalination plant, a thermal storage system is implemented. The type of storage is sensible, which is the simplest one as it only requires one tank with hot fluid and one with cold fluid, and does not involve a phase change or a chemical process.

For the desalination process, the technologies can be divided into thermal, membrane or mixed. Thermal processes mainly use the process of evaporation, as in the case of multi-stage flash and multi-effect distillation. Multi-stage flash is the second most common method of desalination, but now more attention is given to multi-effect distillation, as it allows to work in lower temperatures which avoids the problem of scaling and corrosion. Also, the lower temperatures make it easier to combine with solar energy. Reverse osmosis, which is an example of the membrane process, is currently the most common option. It requires a high pressure and pre-cleaning of the feed for proper operation. It is however not recommended for the Red Sea, characterised by high temperature, salinity and turbidity. An example of mixed solution is membrane distillation, which combines using a membrane and the process of evaporation. It is however still in development, so it is not considered here. There are a few other technologies, such as freezing, forward osmosis or electrodialysis, but they are either very limited in applications or still developing. With those options in mind, multi-effect distillation is chosen as the preferred technology for the analysed system.

3. Model

As it was already described, a multi-effect distillation combined with solar tower and a storage system is considered. The solar tower system combines of the heliostat field and the central receiver. The heat transfer fluid, HTF, used in the cycle is thermal oil Therminol 66. It can be operated in temperatures range of -3 to 345°C [3], which is within the requirement of this system. The operating temperatures range for molten salts (which are the most commonly used heat transfer fluids with solar towers) are very high and such high temperatures are not required for the process of desalination. Regarding the central receiver, the two most common options are external receiver and cavity receiver. An external receiver consists of tubes with HTF placed around the top of a cylindrical tower. A cavity receiver implements a cavity in which a receiver is placed for lower heat loses, mainly the radiative losses. In this case an external receiver is considered. It is simpler and with thermal oil as the HTF the radiative losses are not as severe since the operating temperatures are lower. With the heliostat field, a radial staggered configuration is applied, which minimises the shadowing and blocking loss. For the desalination station, a normal flow as the configuration of operation is considered. It is recommended for the process of desalination, with contra flow being optimal for chemical process and parallel flow for salt manufacturing [4]. The scheme of the system is presented in Figure 1.

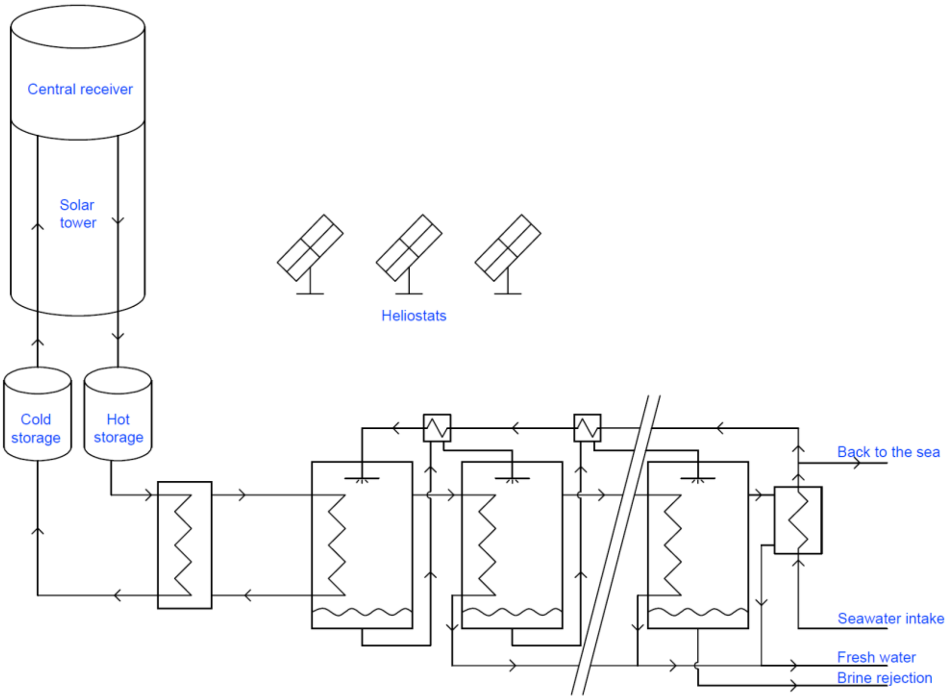

Figure 1 - Simplified scheme of the system: solar tower with heliostat field, thermal storage and desalination station

As it consists of many parts, a model for each part is developed and then combined into one computational code. Since from almost every part of the system heat losses need to be calculated, a general heat loss model from Çengel [5] is applied. The first analysed part is the water heating loop. It connects the heat exchanger and the first effect of the desalination plant. The working fluid in this cycle is water. The losses from the pipes and the heat exchanger are calculated. The heat exchanger of shell and tube type is considered. Next part is the thermal storage system. Two tanks are implemented, one with hot and one with could HTF. The heat losses compose of losses from the bottom, the top and the walls. For the bottom, a model by Suárez et al. [6] is applied. It implements a layer of insulation and two layers of concrete below the tank, with a cooling pipe between the concrete layers. The cooling pipe is used to avoid exceeding the maximum temperature of concrete. For the top and the walls, a general heat loss model is used, with proper formulas for Nusselt correlation depending on the dominating mode of heat transfer and the geometry. Each side of the storage tank is covered with a layer of insulation to decrease the heat losses and the temperature decrease in the tank. For the central receiver, a model of heat losses developed by Li et al. [7] is used, which considers radiative, reflective, convective and conductive losses. To simplify the process of calculations, the model assumes that the temperature of the HTF in the central receiver does not vary, but an average value between the inlet and outlet is used and assumed constant. An important parameter calculated in this process is the receiver surface temperature. It is influenced by the solar power collected from the heliostat field, but also by the mass flow rate of the HTF inside the receiver. In certain conditions, usually when the mass flow rate is low to maintain a constant outlet temperature, the temperature of the receiver surface can become very high. It increases the heat losses, but should it become too high it can also damage the material. If this occurs, the heliostats need to be defocused to avoid damaging the equipment.

For the heliostat field a model developed by Srilakshmi et al. [8] is used. Heliostats are subjected to five types of losses: cosine, atmospheric attenuation, reflectivity, shadowing and blocking and spillage. First, a theoretical heliostat field is created around the central tower. In each cell of the field calculations are performed to find the preferred location of heliostats – maintaining the chosen radial staggered configuration and characterised by minimal losses. The cosine losses are the result of the cosine of the sun's incident angle, and so they need to be obtained for every position in the field and every hour of the year to account for the sun's movement. The atmospheric attenuation leads to decrease of radiation along the path, which is another source of losses from the heliostat. A model for a clear day is applied, since in the analysed region clear days are dominating over hazy days, and the losses are calculated. They are only location dependent, namely they depend on the distance from the heliostat to the central receiver, so they need to be calculated for every location in the field. Solar tower height needs to be included here. It is not known yet but assumed, and later calculated in an iterative process to find a height that provides highest efficiency. The reflectivity losses change with the degradation of the surface of heliostats and depend on their cleanliness. As those parameters are difficult to establish, a constant value over the entire year is assumed. The shadowing and blocking losses are the most complex ones for the heliostats. They depend on time, location in the field and the location of other heliostats. Available methods are very complex and computationally intensive. In simpler analyses, a constant value of shadowing and blocking can be assumed based on existing heliostat fields, and this is the case here. However, neglecting this loss could result in placing heliostats directly next to one another in the theoretical computational field. To account for the gaps, a parameter called packing density is implemented, which is calculated based on the distance from the solar tower. The formulas for packing density are developed based on existing heliostat fields and allow to account for the gaps while avoiding the complex process of calculation of shadowing and blocking losses. The spillage losses concern part of radiation that does not fall on absorbing area of the central receiver. Available methods of calculation are rather complex, and considering those losses are very low, about 1%, also a constant value over the year is applied. As the design desalination power is known, the heliostat field needs to account for all subsequent losses to be able to maintain the operation of the desalination plant. The equivalent capacity of the heliostat field is calculated, which considers the losses and also the storage time. Based on that capacity the calculation of all losses for the heliostats are performed. From the theoretical field locations with highest efficiency are chosen and used in the calculations of collected solar power. The height of the solar tower is determined to maximise the amount of collected solar power.

The desalination system model is implemented from Filippini et al. [9]. Figure 2 shows the first two effects of the desalination system.

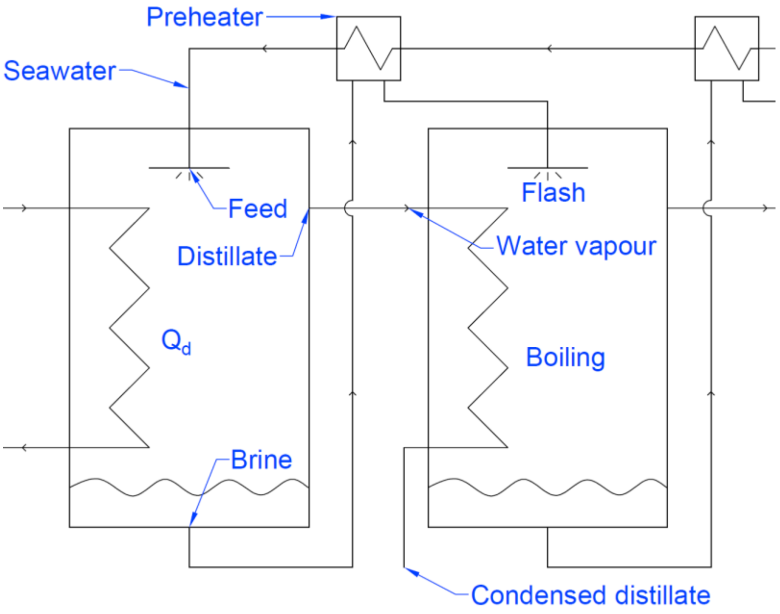

Figure 2 - Scheme of the first two effects of the desalination station

The number of effects is established to maintain the recommended temperature difference between the effects, and the amount of distillate obtained from each effect is calculated. In each subsequent effect a lower boiling temperature and a lower pressure is maintained. The distillate is obtained from two processes: flashing, which results from lower pressure and resulting lower boiling temperature, and boiling. For the desalination process, a constant amount of heat is delivered to the first effect. The amount of fresh water produced is depending also on parameters of the seawater, so it is not constant throughout the year. A monthly variation of the seawater temperature is considered to observe the change of fresh water production over a year.

Every part of the model is validated by comparing the results from the simulation to the results from the source papers, and all have shown to be around 90% accurate and more, indicating a proper implementation of each part of the system. As the system is rather complex, a short description of the process of calculations is given. All the inputs are collected from a CSV file. First, the efficiency of the heating water cycle is calculated. Then, the heliostat field calculations are performed based on a CSV file containing the weather data [10]. The design power of the field is assumed and then recalculated, should it be necessary. The heliostat field is established and the efficiencies calculated, which allows to obtain the hourly solar power collected from the field. Then the efficiency of the central receiver is calculated for every hour of operation, based on the power delivered from the heliostat field. To maintain a constant temperature of the hot HTF fluid, depending on the solar power absorbed the mass flow rate must be controlled and adjusted properly. The next part of calculations concerns the thermal storage system. A mass balance is performed based on the incoming flow from the central receiver and leaving the tank for the heat exchanger. The losses for this part are particularly important. Due to the heat loss the temperature in the tank will decrease, which will influence the mass flow rate to the heat exchanger and impact the mass balance.

To maintain a constant operation of the desalination system, it is crucial that the design heliostat power, the storage tank dimensions and the initial level in the tank are proper. With many efficiencies changing hourly with the weather, finding and exact value would be very complex, so they are assumed. If at any point in the calculations the tank becomes completely full, its height is increased by 10% and calculations repeated. Should it become empty, the initial level is increased by 10%. If the level at the end of the year is much lower than at the beginning, it suggest that the system would not be sustainable in the upcoming years, so the design power of the heliostat field is increased by 0.5 MW. Finally the model of desalination is applied to obtain the amount of distillate produced in each month.

4. Results

Two cases are considered. First is the reference case, with location in Saudi Arabia. The second is a change of location to Albufeira in Portugal. Applying two cases allows to observe the change of the results and to draw conclusions on operation of the system. Table 1 shows the key results – the tower height, the design heliostat field power and the storage height – for both cases.

Table 1 - Comparison of the results for Saudi Arabia and Portugal

Parameter	**Saudi Arabia**	**Portugal**
Tower height, m	31.42	38.53
Design heliostat power, MW	11.3	13.8
Storage height, m	16.96	32.92

It can be observed that in Portugal a higher design heliostat power is required. As the average direct normal irradiance, DNI, is lower in Portugal than in Saudi Arabia, higher design heliostat power is needed to accommodate for different weather conditions. The solar tower height is also greater in Portugal. It is mainly influenced by the design heliostat field power, so it was expected to also be higher. Due to larger variation of DNI over a year in Portugal than in Saudi Arabia, the storage tank needs to be bigger to store more hot HTF in the summer to allow for continuous operation in the winter.

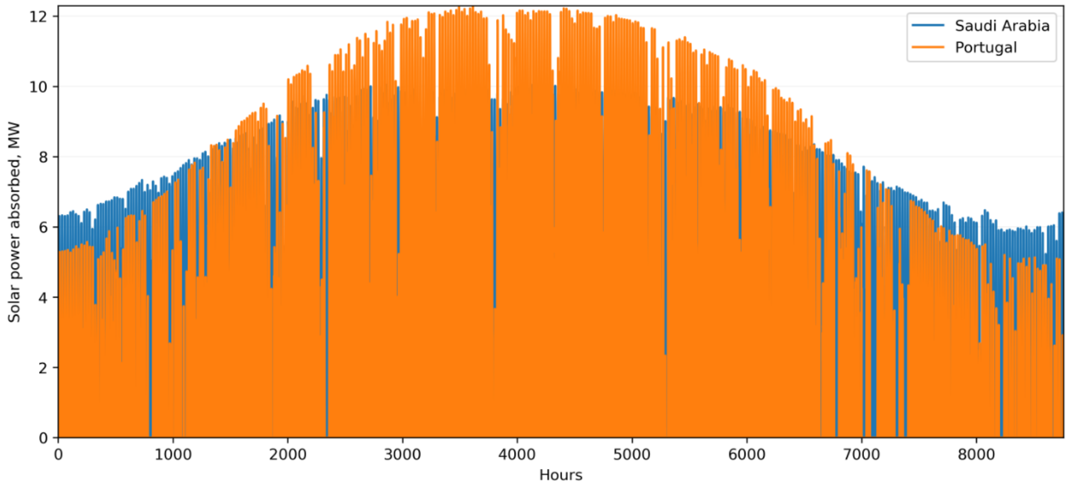

Figure 3 – Solar power absorbed in Saudi Arabia and Portugal

Figure 3 presents the solar energy absorbed in Saudi Arabia and in Portugal. Even though the design heliostat field power is greater in Portugal, in the winter months still more power is absorbed in Saudi Arabia due to higher DNI. As Saudi Arabia is located closer to the equator, the values of DNI remain high throughout the year and are not fluctuating as much as in Portugal. In Portugal more frequent interruption in absorbed power are present. As it was described, if the surface temperature of the receiver becomes too high, the heliostats need to be defocused. Generally this is done when the solar power collected is below 25% of the design power. With greater variation of DNI, it is more frequent in Portugal. That issue could potentially be improved by changing the parameters of the central receiver, as for this analysis only the location was changed.

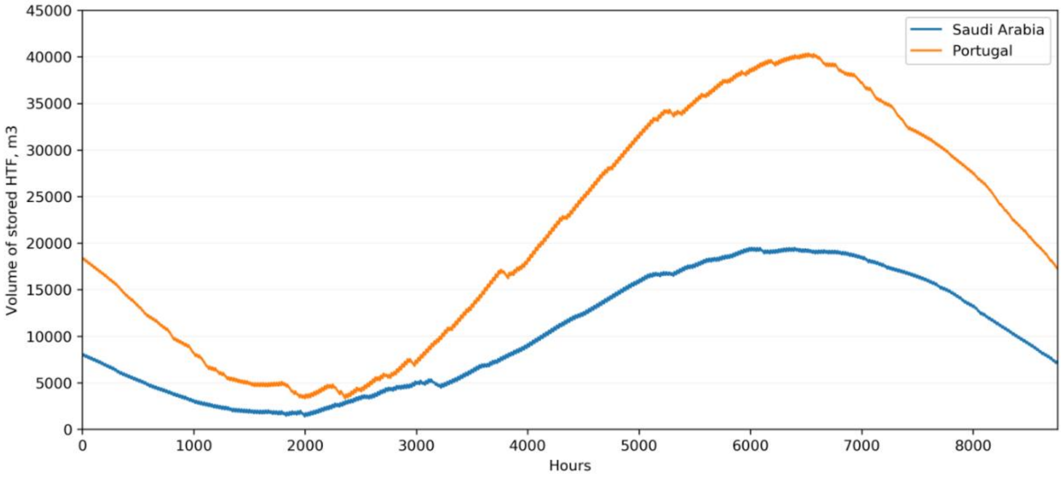

Figure 4 - Volume of stored HTF in Saudi Arabia and Portugal

Figure 4 shows the volume of stored HTF for both cases. As already described, the tank needs to be larger in Portugal, and so it reaches a much higher volume of stored fluid in the summer. The level at the beginning of the year and at the end is similar in both analysed cases, indicating that the system is sustainable and capable for continuous operation. It can be noticed that the lowest level in the tank is lower in Saudi Arabia than in Portugal. It suggests that the initial level for Portugal was too high and could be decreased. This is the result of the computation process, which does not find an exact value but an estimate, which is then increased by 10% if it is too small. The value of the initial level could be improved by changing the increment to 5%, but that would increase the computation time significantly since the process of calculations is rather complex.

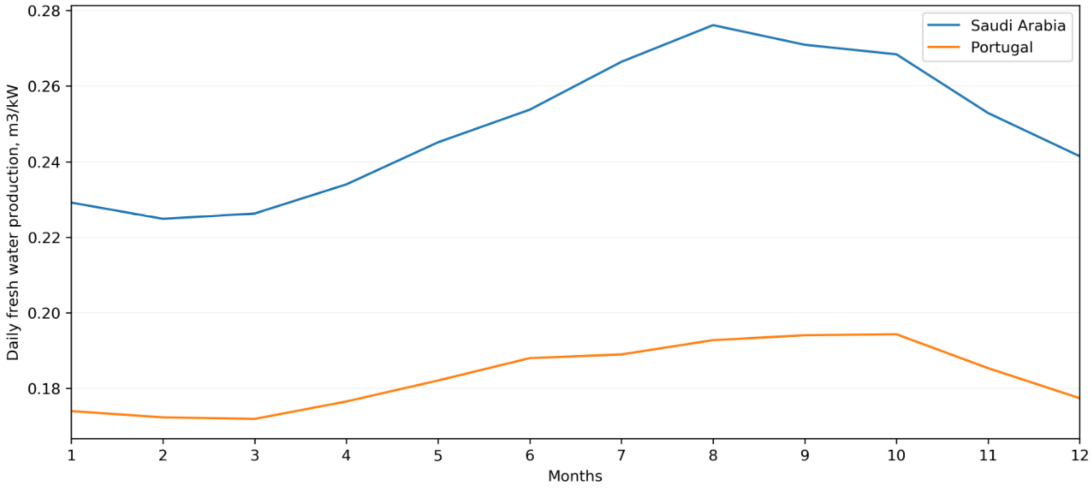

Figure 5 - Fresh water production over a year in Saudi Arabia and Portugal

Figure 5 presents the fresh water production over a year in both cases. As it can be observed, in Saudi Arabia much more water is obtained. The reason for that is the seawater temperature difference - it is higher in Saudi Arabia than in Portugal. As the boiling temperature in the first effect is fixed, it is easier to bring the feed to this temperature when the seawater is warmer, and so the mass flow rate can be higher resulting in greater fresh water production. The yearly variation curve is similar – it increases in the summer months and decreases in the winter months, following the seawater temperature change over a year.

Additionally, as the system requires over 30 inputs, a parametric analysis was performed to observe their influence and importance. Each parameter was increased and then decreased by 10% and the results analysed. An influence on the capacity of the heliostat field, the fresh water production, the average temperature decrease in the hot storage tank, the storage tank height and the yearly solar energy absorbed was observed. The most significant parameter is the design power of the desalination system, as it is the base for all calculations and so it impacts all the results. For desalination, the temperature of the brine, hot and cold water are crucial. For the tank volume and the temperature decrease almost all parameters carry some influence, the most important being the temperature of the hot HTF fluid and the insulation properties. For the energy absorbed, it is once again the desalination capacity, along with the hot HTF temperature and all parameters influencing the efficiency of the central receiver – namely the geometric properties and the emissivity of the surface of the central receiver.

5. Conclusions

The thermodynamic analysis performed here yields some interesting conclusions. Although a concentrated solar energy desalination plant is a very interesting solution to the problem of limited fresh water resources, it is still dealing with some problems. The main conclusions are as follows:

- The location of the plant is particularly important. Saudi Arabia is preferred over Portugal due to higher and more stable DNI and higher seawater temperature.

- Water production is not stable because of the changes of the seawater temperature, making the desalination plant less prone to be considered a reliable water source. A system which does not provide constant amount of heat to the first effect but aims for a constant water production could be a better solution.
- Despite the good weather conditions in Saudi Arabia, still the heliostat field power had to be over five times greater than the desalination power to allow for continuous operation.
- Large area requirement for the heliostat field is not a problem in Saudi Arabia, but can be an issue in other countries, or when more plants need to be built.
- The system is assessed as sustainable – the level of HTF in the tank at the beginning and at the end of the year is at a similar level. A perfect fit would increase the computation time significantly, but also since the weather conditions may change in the next years, it would be only valid for one year. A simulation over a few years could better assess the sustainability of the system.
- An optimization of the process could be performed. Most parameters have impact on many parts of the system, so it would be a complex process. It could result in better efficiencies of subsequent parts and overall better performance of the system. For example, the central receiver had a problem of exceeding the maximum surface temperature when the second location was analysed. Changing the geometric or operating parameters could help resolve that problem.
- The focus in the analysis was put on the thermal aspect and some factors were not considered. The pressure losses occur due to the flow, especially in the central receiver and heat exchanger, where small diameter of tubes is applied. Pumps are used to maintain the flow of fluids and proper pressure in the effects of the desalination plant. The pumps use electrical energy, which was also not considered here.

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