A DIRECT STEAM GENERATION SOLAR POWER PLANT WITH INTEGRATED THERMAL STORAGE

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Abstract

For the future market potential of parabolic trough power plants with direct steam generation (DSG) it is beneficial to integrate a thermal storage system. Heat storage media based on phase change materials (PCM) offer heat transfer at constant temperatures needed for the evaporation process. Different options for a plant layout are presented and discussed. The interactions between the three subsystems solar field, power block and thermal storage are analysed and boundary conditions arising from the thermal storage system are identified. Compared to a system without storage the number of operating points increases significantly since different combinations of storage charge and discharge operation go along with a varying power output of the solar field. It is shown that the large number of theoretical operating points can be reduced to a subset with practical relevance. Depending on the live steam parameters a reheat is necessary within the power block. Compared to parabolic trough fields with a single phase heat transfer medium like oil a special heat exchanger configuration is needed for a DSG plant. Different alternatives based on available technologies are presented and evaluated.

Keywords: solar thermal power plant, direct steam generation, thermal storage.

1 Introduction

Solar-thermal power plants are one of the key technologies for the production of electricity from renewable energy resources. In parabolic trough collector rows oil as a heat transfer fluid is heated by concentrated solar irradiation. The thermal energy is transferred to a water-steam cycle. There, steam drives a steam turbine. Although such plants with a total power of 354 MW have successfully been operated since the 1980’ in California and are now being built in Spain and the US, the growing interest in green technologies provokes the question on limitations and optimization potential of this technology. As known from conventional power plants, the efficiency of the thermal cycle increases with its steam parameters. Unfortunately, current technology does not permit a further increase of the solar field outlet temperature since the oil used as a heat transfer fluid reaches its chemical stability at about 395 °C and, therefore, also the main steam temperature is limited. Several alternatives are under discussion. One of the most interesting ones is the direct steam generation in the collector field[1]. Instead of the two loop system used so far the water is directly evaporated and superheated in the solar field which makes the oil-water heat exchanger needless. The key advantage is seen in the potential increase in upper process temperature to values of 400 °C to 550 °C[2]. Demonstration and optimization of key components for this technology has been done on a 700 m collector loop on the Plata Forma Solar in Almeriá (Spain) and in several research projects in the last years[3]. For solar thermal power plants a thermal storage system allows a higher utilization of the power block and the ability to produce electricity on demand. For the oil based plants heat can be stored in two tank systems containing the heat transfer fluid itself or molten salt[4]. The latter option requires oil/salt heat exchangers. The pinch point topic for the water steam cycle makes it unattractive to use such storage systems in a direct steam generation plant. Adapted to the three sections for preheating, evaporation and superheating a three component storage system based on sensible and latent heat storage is advantageous. The heat needed for evaporating the water is stored in a latent heat material like salt[5]. During charging, the salt melts at a constant, material-depended temperature that has to be chosen some Kelvins below the saturation temperature of the steam that delivers the heat. When heat is taken out for evaporating water the salt freezes, again at constant temperature. For the direct steam generation, $NaNO_3$ is an interesting salt material with a melting temperature of 306 °C. Assuming a driving temperature difference of 10 K between steam cycle and storage system, the steam has to condensate at 316 °C while charging and has to evaporate at 296 °C during discharge. By the vapor pressure curve, the saturation temperature is directly linked to an operating pressure (107 bar at 316 °C, 81 bar at 296 °C). That means that a higher steam pressure is required for charging the storage than for discharging it. This has significant impact on the design of the coupling between solar field, storage system and power plant. For higher steam pressure, a second phase change material, KNO_3, is available which results in steam pressure for charging of 156 bar and for discharging of 116 bar. In the following, the configuration 110 bar/400 °C will be discussed in detail while power block data are also provided for a 156 bar/500 °C configuration.

2 Analysis of plant configurations

Based on the available phase change the solar field outlet pressure at nominal conditions is set to 110 bars. In addition to the 107 bar necessary for the heat transfer into the PCM storage 3 bar are considered as a pressure loss in the connecting pipes. The steam temperature is chosen to 400 °C since absorber pipe coatings are currently available up to this temperature. For main steam parameters of 110 bar/400 °C, a reheat turbine is necessary to avoid a high moisture content at the turbine outlet, see also section 4. The nominal electrical power of the system is 50 MW according to the feed-in-structure in Spain. One possible design, referred to as the reference configuration, is shown in Figure 1. The solar field is operated in recirculation mode with a phase separator between pre-heating/evaporation and superheating sections. An injection cooler is placed before the last collector of each row to stabilize the steam temperature. The steam feeds the high-pressure turbine (HP), is re-heated and directed through the low-pressure turbine (LP). The thermal storage system is arranged similar to the solar field with a sensible heat storage system for the pre-heating and superheating and a latent heat storage system based on a PCM for evaporation and a sensible heat storage system for superheating. For charging, steam from the solar field is directed through the storage system in reverse direction. The steam is cooled down in the superheating section, condensed in the evaporation section and cooled down in the pre-heating section. The condensate water is mixed with the feed water from the power block and fed into the solar field. For charging the storage, the field outlet pressure has to be maintained at 110 bar. As stated above, the steam pressure during discharge cannot exceed the value of 78 bar since a driving temperature difference between PCM material and liquid is required to obtain high heat flux. This represents a boundary condition for the combined operation of solar field and storage.

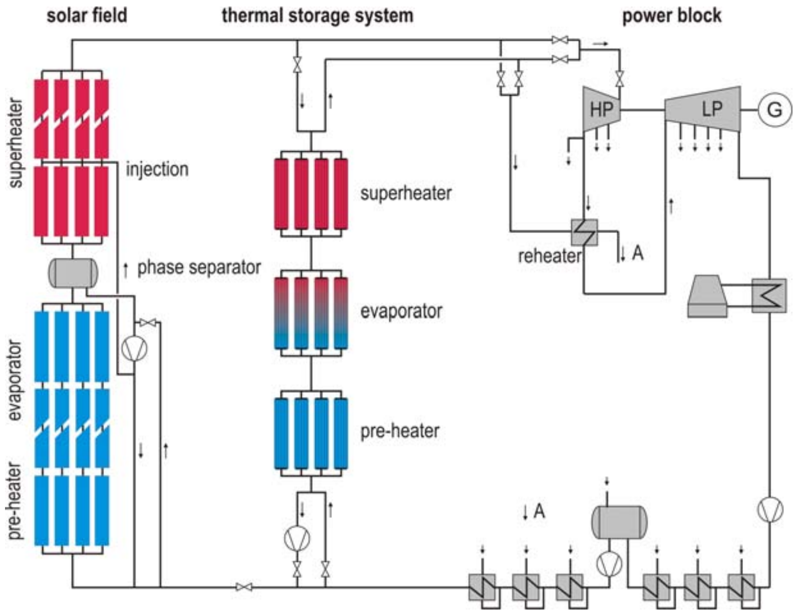

Figure 1: Reference plant configuration

The integration of steam from the storage is, due to this boundary condition, not as easy as in a solar thermal power plant with indirect steam generation. In such plants, steam from the oil-water/steam heat exchangers and steam from the storage have the same pressure level and, therefore, can be mixed in front of the HP-turbine. In power plants with direct steam generation, steam generated in the solar field and steam generated in the storage have a significant pressure difference (depending on the operating point). Because of this pressure difference they cannot be mixed without throttling the high pressure steam.

One possibility to integrate steam from the storage into the cycle is to operate the system in sliding pressure mode, if steam is taken from both boilers, the solar field and the storage. This is done by reducing the pressure at the feed water pump until both steam paths have the same pressure and can be mixed in front of the turbine. To integrate the steam from the solar field, its pressure has to be at least equal to the storage discharge pressure. A modified sliding pressure operation of the solar field is therefore preferred for a plant with storage system. It is characterized by two constant pressure levels, one at 78 bar for storage discharge at low solar field output and one at 110 bar for storage charge during high solar field output. In between, the field is operated in sliding pressure mode to allow smooth transition. In any case, the turbine inlet pressure during storage discharge is limited to the discharge pressure of the storage, which, in the 400 °C configuration, is 78 bar. Since the volume flow through the turbine is limited to the design volume flow (acc. Stodola) the max. mass flow through the turbine corresponds to the current main steam pressure. If the main steam pressure is limited to 78 bar (due to storage operation), the mass flow must be reduced, too. A reduced mass flow in the turbine goes along with reduced power and electrical output. Due to these basic physical effects with this plant configuration the design power cannot be maintained during long low-irradiance periods by means of the storage.

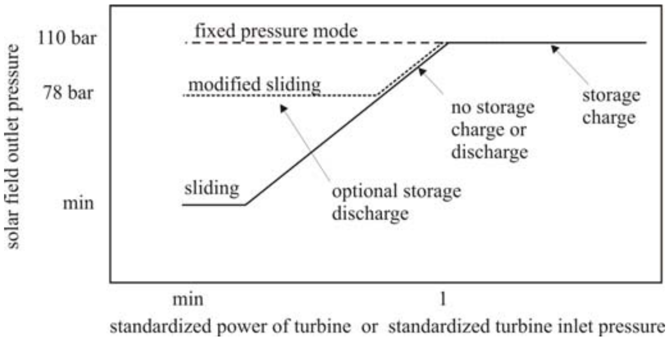

Figure 2: Operating modes for the solar field

Another possibility that partly overcomes this limitation is to feed steam from the storage into a later stage of the HP-turbine, which has the adequate pressure level, see Figure 3. In a combined operation mode (steam from the solar field and from the storage) the first part of the HP-turbine, from inlet up to the feed-in of the storage steam, is working in part load and therefore with lower efficiency than in the design case. Due to mechanical and aerodynamical reasons, the maximum feed-in from the storage into the turbine stage has to be limited. If the fraction of steam from the storage is higher than the limit, the steam from the storage has to be fed into the first turbine stage.

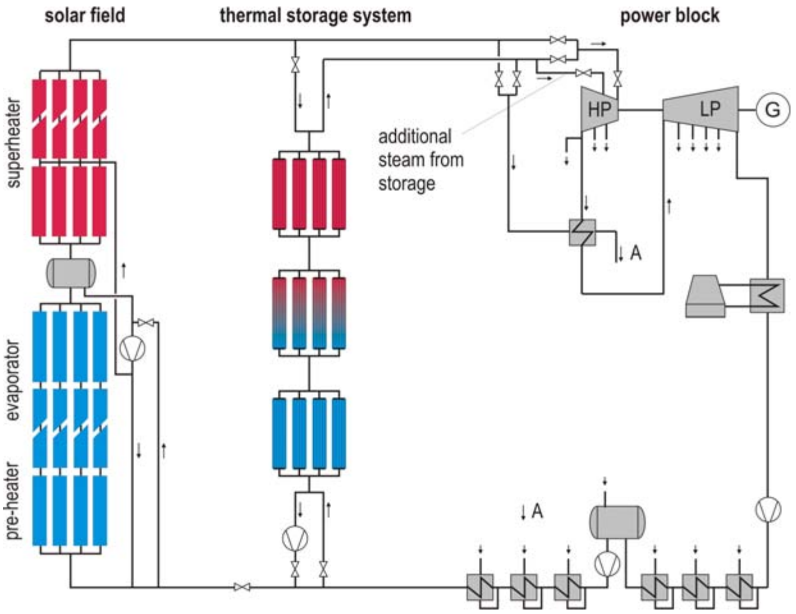

Figure 3: Plant configuration with storage feed in at lower pressure stage

Concerning the reheat system, reheat directly in the solar field would be an equivalent to a conventional fossil fired power plant. This implies separate collector rows with headers going into and coming out of the field. Since the reheat steam pressure is low the expected pressure drop in the solar reheat field reaches 10 bar. With such a high pressure loss over the reheat solar field a configuration with direct reheating in the solar field makes no sense, since the efficiency loss is too high. The alternative is to use a part of the main steam to reheat the steam by a heat exchanger as illustrated in Figure 1 and also in Figure 3. A detailed discussion of the heat exchanger

configurations is given in section 4. If a hybrid fossil-solar plant is considered another option would be to take the heat for the reheat from a fossil boiler. Since hybrid plants are not allowed under Spanish feed-in laws this option is not considered further.
A system with reheat by a heat exchanger and steam integration by mixing the steam in front of the turbine is chosen as a reference configuration for this study.

3 Operating points

The electricity output of a conventional steam power plant is controlled by the heat input into the system. Each heat flow corresponds to one pre-defined operating point. Slight variations from the operating point occur during transients or as a result of changes in the ambient conditions. In a solar thermal power plant without storage the same applies as it is illustrated in Figure 4. The whole space of possible operating conditions is represented by a single line. When including a thermal storage, a large number of additional operating points are added. The single line from Figure 4 is expanded to a large area, which is mainly parameterized by the storage charge/discharge power. The difference between turbine power and solar field power is the power sent to or received from the storage. Several areas are shown in Figure 5 that do not allow operation of the plant. Here, the limitation of the PCM-based storage system reduces the maximum power during storage discharge. Since the whole system has to be designed to work in all possible operating points one is interested in reducing the complexity by selecting only relevant areas. Figure 6 shows how the area of theoretical operating points can be limited to a number of lines by this approach.

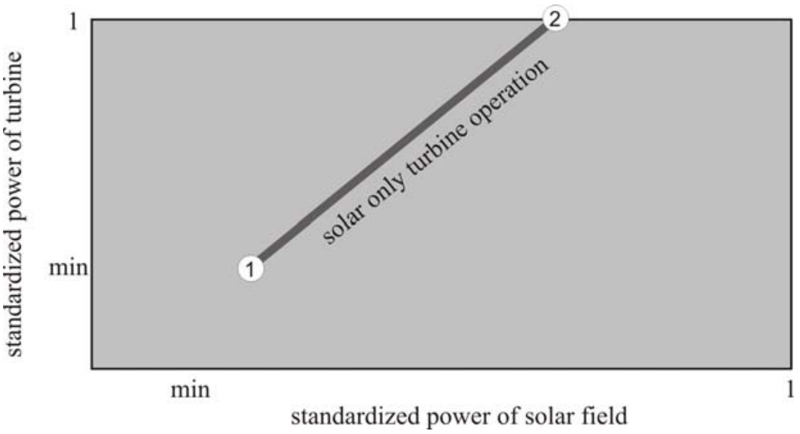

Figure 4: Operating point diagram for a plant without thermal storage

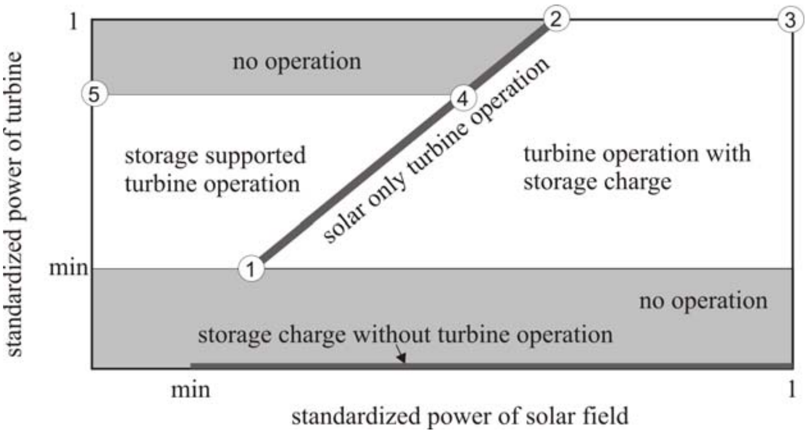

Figure 5: Theoretical operating point diagram for a plant with thermal storage

A strong simplification can be reached by assuming that an arbitrary combination of storage charge and turbine operation will not occur. If it is useful from the economic point of view to sell electricity at a particular point in time, the turbine is run with maximum load and only surplus energy from the solar field is stored for production at a later time. The area named “turbine operation with storage charge” can thus be reduced to the line 2-3. If it is better to shift electricity production into the future, the heat from the solar field is stored (line 14 to 9) and only the surplus is directed to the power block (line 13-7-8). The surplus must at least be the minimum load of the turbine (line 13-7). In a similar way, the area “storage supported turbine operation” can be reduced. If electricity production is desired at a certain point in time with little or no input from the solar field the turbine will be run on the maximum power that can be achieved at storage discharge pressure (which is lower than the design pressure of the turbine). An amply dimensioned storage can sustain that power even when the contribution of the solar field drops to zero (line 5-4). With a smaller dimensioned storage, the turbine reaches maximum discharge mode power only with input from the solar field (line 10-4); below, turbine power drops to peak storage discharge power (line 10-11-12). (A potential decrease of discharge power of the storage with discharge time is not accounted for in this consideration). If electricity production is shifted to a later instant it might be useful to run the turbine on minimal load to keep it warm (line 1-6). Comparing Figure 4 with Figure 6 clearly illustrates how the integration of a thermal storage system increases the complexity of the system both from the technical and control point of view.

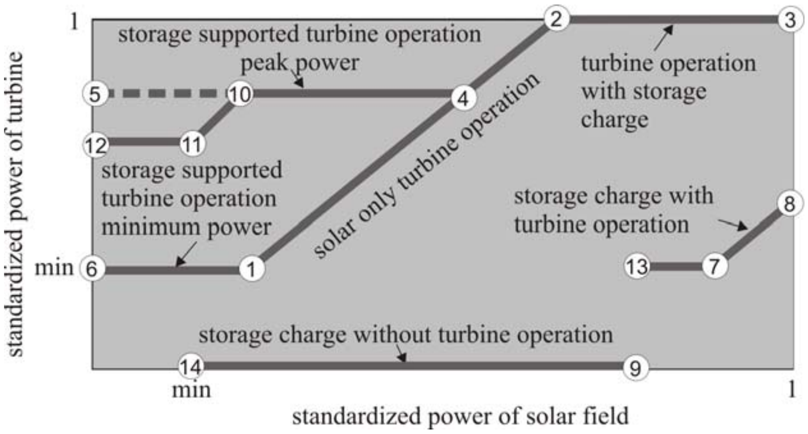

Figure 6: Practical operating point diagram for a plant with thermal storage

4 Power block optimization

Fossil fuel fired power plants can optimally follow the grid power demand by adjusting the heat input. In contrast, the power output of solar thermal systems is more or less given by the solar heat input, at least until sufficient thermal storage is available. This entails different requirements such as more frequent start-ups and fast load changes. Therefore, the power block has to be modified or at least adapted to these special conditions.

Within this project 50 MW_{el} power block concepts, which are optimally adapted to the direct steam generation and using state of the art technology, are developed. They are designed for main steam parameters of 400 °C/110 bar and 500 °C/156 bar at the inlet of the storage system. The 500 °C/156 bar system displays a possible future potential of the DSG with PCM storage. Due to the phase changing material, which is today seen as most suitable for a 500 °C DSG power plant, the main steam pressure at the storage system has to be 156 bar. Hence, a generic turbine based on an extrapolation of the Siemens SST-700 was used for the power block layout. For the 400 °C/110 bar system, the solar steam turbine SST-700, Figure 7, was selected, which today is used in every parabolic trough power plant under construction worldwide (table 1.). Its advantages are high efficiency also in part load, fast start-up, fast load changes and a good price/performance ratio. Both systems studied are designed with a wet cooling tower and for the ambient conditions of Tabernas (Spain). Essential optimization parameters are the final feed water temperature, the reheat configuration and the implementation of the storage system.

The determination of the optimum final feed water temperature (FFWT) is a compromise between the thermodynamic efficiencies of the power block and the solar field. This temperature should be as high as possible (technically dependent on the number of feed water preheaters) for highest thermodynamic efficiency of the power block, because the mean temperature of heat input is raised and the conversion losses are minimized. In the solar field, however, a high FFWT raises the thermal losses and, therefore, lowers the solar field efficiency. For the SST-700 turbine, three FFWT depending on the number of HP-preheaters are evaluated. As basic layout, three LP-preheaters, one feed water tank and one HP-preheater are chosen leading to an optimal FFWT of 205°C. For the second layout, two HP-preheaters and for the third layout three HP-preheaters are used. For these layouts, the optimum FFWT was evaluated to 245 °C and 260 °C. Compared to the basic layout, a noticeable efficiency increase of the conventional cycle is determined for both options.

An additional parameter for the solar field efficiency is the direct solar irradiance, see Figure 8. Between the relevant FFWT of 200 °C and 260 °C the solar field efficiency decreases for a direct irradiance of 1000 W/m² by 0.4 percentage points and for an irradiance of 400 W/m² by 0.6 percentage points. This first analysis shows that for a FFWT of 260 °C the highest overall plant efficiency at the design point is achieved which is slightly higher than the one at 245 °C. To determine an optimized FFWT the part load behavior of the power block and the solar field need to be considered as well. This has to be done, as a next step, by calculation of the cumulated electricity generation (e.g. over one year) varying the FFWT.

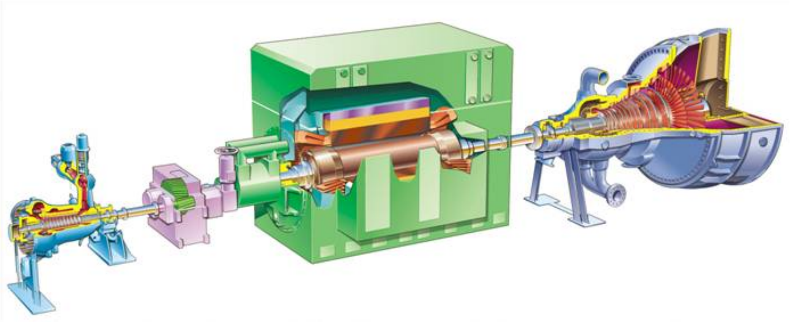

Figure 7: Sketch of Siemens SST-700 steam generator set

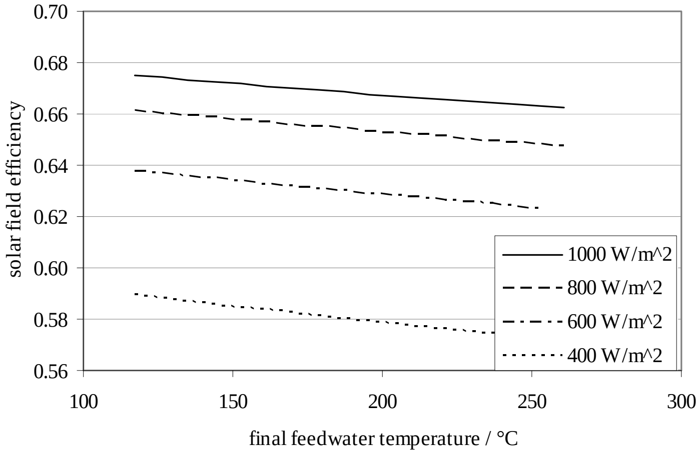

Figure 8: Solar field efficiency at 100 bar/400 °C for a system with 50 parallel loops

Project Name	**Site**	**Rated Power**
Nevada Solar One	Barstow, USA	1x74 MW
Andasol I/II	Guadix, Spain	2x50 MW
Ibersol Ciudad Real	Puertollano, Spain	1x50 MW
ExtreSol I/II	Spain	2x50 MW
Solnova I-IV	Sanlucar, Spain	5x50 MW
Acciona I	Spain	1x50 MW
further projects	Spain	10x50 MW

Table 1: Reference list for solar steam turbine SST-700

Due to the main steam parameters of a solar thermal power plant, in particular for the 400 °C reasonable today, a reheat turbine is necessary to avoid an unacceptable moisture content at the turbine outlet. The reheater has to provide a preferably high outlet temperature at low pressure loss. To realize such reheat in a DSG power plant, a steam-steam heat exchanger with condensation is proposed. The evaluation of other possibilities like fossil firing (restricted by legislation or economics) or a separate solar field for reheating (very high pressure loss) shows, that these systems do not reach the technical performance of the steam-steam heat exchanger with condensation.

Contrary to solar thermal power plants with indirect steam generation, in case of DSG, the outlet reheat temperature feasible by a steam-steam heat exchanger is not as high as the main steam temperature. The reason is, that by the use of the condensation energy, a pinch point problem arises in the heat exchanger. Due to that, the reheater is not used to increase the cycle efficiency (normally done for example in coal fired power plants or solar thermal power plants with indirect steam generation), because the mean temperature of heat absorption can not be raised. For the task of avoiding an high moisture content at the end of the LP-turbine a reheat temperature of approx. 300-330 °C is sufficient depending on the steam pressure at the LP-turbine inlet. A parallel-flow heat exchanger layout for the 400 °C/110 bar system with a minimum temperature difference of 12 K is shown in figure 9. Such a layout makes sure, that the moisture content at the turbine outlet is within its limits. The parallel-flow heat exchanger guarantees, that no pinch point problem can occur.

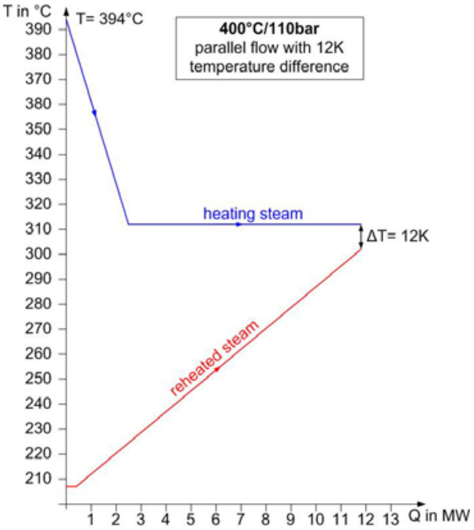

Figure 9: Design of a parallel-flow heat exchanger with a minimum temperature difference of 12 K

For both systems, the 110 bar/400 °C and the 156 bar/500 °C configuration, a final feed water temperature of 260 °C (three LP-preheaters, one feed water tank, three HP-preheaters) and a steam-steam reheater with condensation are chosen. A heat flow diagram for the 400 °C/110 bar system is shown in Figure 10. First results of the power block optimization are shown in Table **2**. Comparing the design cases of both systems the gross efficiency of the 500 °C/156 bar power block with 42.4% is considerably higher than the gross efficiency of the 400 °C/110 bar power block with 40.1% due to higher main steam parameters.

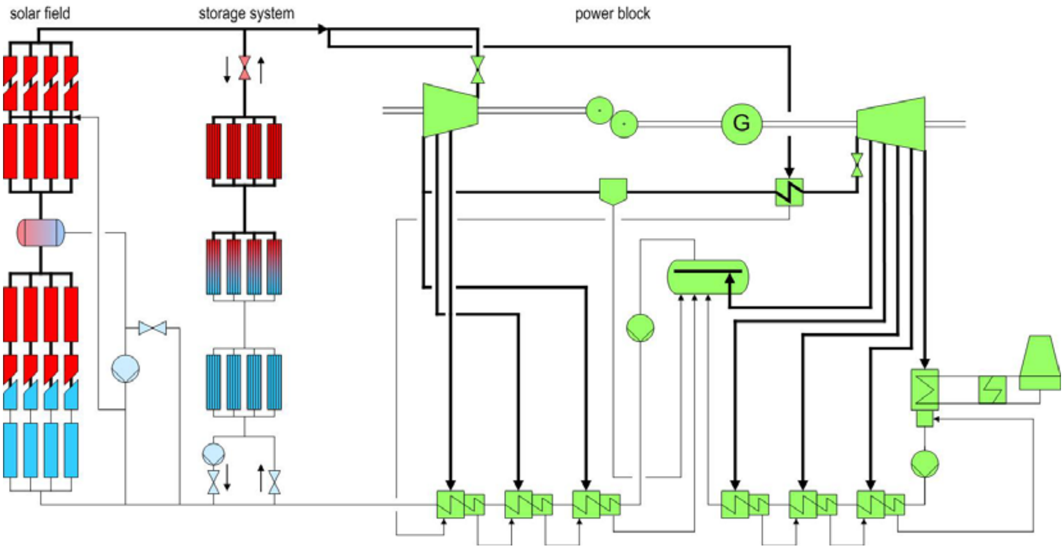

Figure 10: Heat flow diagram for the 400 °C/110 bar system

		400 °C/110 bar	500 °C/156 bar
Power (gross)	MW_{el}	50	50
Final feed water temperature	°C	260	260
Main steam temperature	°C	400	500
Main steam pressure	bar	110	156
Reheat outlet temperature	°C	302.3	329.2
Reheat outlet pressure	bar	17.0	18.0
Power block efficiency (gross)	%	40.1	42.4

Table 2: First results of power block optimization

5 Conclusions and outlook

The integration of a thermal storage system increases the complexity of a direct steam generation solar power plant. A reasonable reduction of the number of operating points can be achieved if only relevant operating conditions are considered. The usage of a PCM storage system for the evaporation of water implies that the pressure for discharge is significantly lower than the pressure level required for charging. Due to the turbine characteristics a reduced power output goes along with reduced pressure during discharge of the storage. Two power block configurations for the steam parameters, 110 bar/400 °C and 156 bar/500 °C, are suggested based on a commercially available steam turbine. For both configurations a reheat system is necessary to avoid high moisture content in the low pressure turbine. High pressure losses preclude the reheat directly in the solar field. A reheat based on a steam-steam heat exchanger is suggested making use of main steam and extracted steam from the high pressure turbine. Due to the pinch point problem within this heat exchanger the reheat temperature will be significantly lower than the main steam temperature. The work presented demonstrated that there are significant differences in the plant layout of a parabolic trough power plant with direct steam generation compared to a plant with indirect steam generation (oil system).

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All pressure values in the text are given as absolute pressure.